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BRITTLE FRACTURE TESTS ON SHIP PLATE STEELS

by

Edward L. Yordy

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SYNOPSIS

This report contains a description and the results of two types of tests conducted on ABS Class C (normalized) ship plate steel to determine the brittle fracture characteristics of the steel. The effect of specimen thickness and geometry on the transition temperature as evaluated by various criteria is examined, and the effect of variables in testing procedures such as notch depth and radius, and loading rate is briefly discussed. A description of testing setups and procedures, as well as copies of the data collected and the methods used to obtain the various transition temperatures, is included. Finally, the results are compared with what would theoretically be expected, and conclusions are drawn.

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1. INTRODUCTION

The problem of structural failure due to brittle fracture is not new. Technical papers dating back to the latter part of the nineteenth century make references to the brittle fracture of steels. Since 1856, when steel first became available in larger quantities for structural use, a great number of failures has occurred at stresses far below the design capacity of the members involved. In the earlier years, when the problem of brittle fracture was even less understood than it is today, there is little doubt that many of the service failures were due to this phenomenon. Strangely enough, it was not until the 1940s, when the incidence of these failures hit a new peak, that a really serious investigation of this problem got underway. The high rate of failures at that time is considered to be the result of several circumstances.

Production requirements of merchant ships during World War II became vastly higher, and with this increase in production it was necessary to use unskilled and inexperienced labor to meet production schedules.

When these unskilled workmen were utilized to prepare and weld structural components, the end result was frequently a structure which had welding or structural defects that acted as stress raisers which could trigger brittle fracture at low ambient temperatures. These so called Liberty Ships accounted for many failures in the mid-forties.

In connection with research to be done on this subject, the Metallurgical and Civil Engineering Departments of Lehigh University have undertaken a series of tests, the purpose of which is to collect experimental data on the subject of brittle fracture transition temperatures as influenced by test specimen geometry and thickness, and to try to obtain theoretical relationships which will be useful in projecting the results obtained to a point where they can be correlated with structures actually in service.

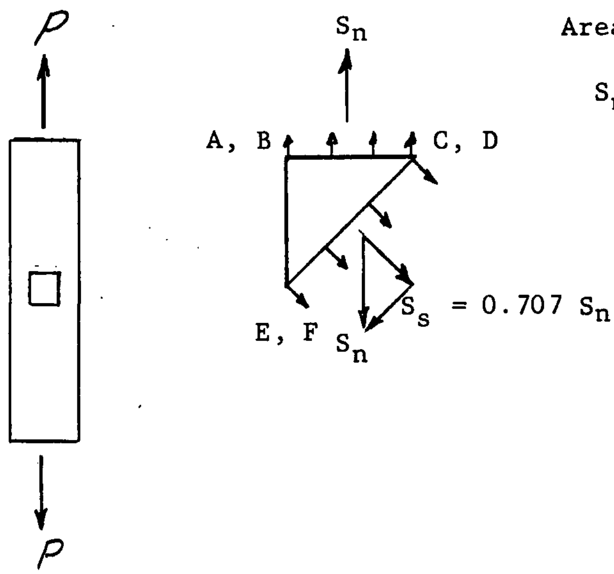
Special mention should be made of Bethlehem Steel Company, which supplied the ABS Class C normalized steel for this project, and of United States Steel Company, which will supply "T-1" high strength steel for further investigations.

The project is under the general direction of Dr. R. D. Stout, Dean of the Graduate School of Lehigh University. Dr. Stout offered much assistance throughout the testing program in helping to establish and evaluate the different criteria which were used. Acknowledgment is also in order for Charles Roper, a Metallurgical Research Assistant, who performed the testing operations with the author of this paper and who will continue with further tests in the future. Mr. Roper will make some other phase of this study the thesis topic for his M. S. degree. Professor Samuel J. Errera should also be commended for his guidance, assistance, and helpful criticism in helping to overcome both the technical and practical problems involved in carrying out this project work and the subsequent writing of this paper. Last but far from least, thanks must be extended to Mrs. D. F. Fielding, whose typing and suggestions were of much assistance in the preparation of the final script.

2. A DISCUSSION OF THE THEORY OF BRITTLE BEHAVIOR

The general principles of brittle fracture indicate that any loading condition which involves a low ratio of maximum shearing stress to maximum normal stress will tend to promote brittle fracture in steel. This principle can be strikingly illustrated by considering a mild steel bar at the temperature of liquid nitrogen (-320° F.). If this bar is subjected to a tensile load, it will fail in a brittle manner. The diagram in Fig. 2.1 shows that the ratio of maximum shear stress to maximum tensile stress in this case is one-half. However, if the bar is tested under the same conditions in torsion, we will obtain a completely ductile type failure. In this case the ratio of maximum shear stress to maximum tensile stress will be seen to be equal to one, as shown in Fig. 2.2.

From this brief discussion, it can be surmised that if some condition is introduced into structural steel which tends to produce a low ratio of maximum shear stress to maximum tensile stress, then brittle fracture will occur more easily. In the tests which were carried out, then, the ratio which enhanced the possibility of brittle fracture was brought about by the presence of a notch. Although the exact value of this ratio is difficult to determine, it is much less than the one-half mentioned above, in order that the transition from ductile to brittle failure can be made to occur in a temperature range



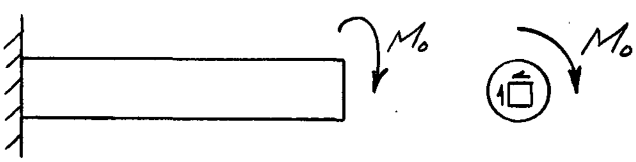
Area C E F D = 1.414 Area A C D B

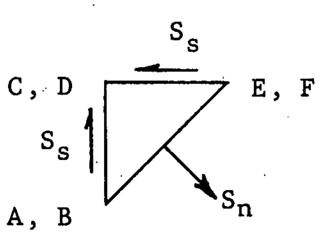
S_n x Area A C B D = $\frac{S_s}{.707}$ x 1.414 Area A C B D

$S_n = 2\ S_s$

$\frac{S_s}{S_n} = \frac{1}{2}$

Fig. 2.1 RATIO OF MAXIMUM SHEAR STRESS TO MAXIMUM TENSILE STRESS IN AXIALLY LOADED BAR





Area A B D C = Area C D F E = 0.707 Area E F B A

2 x S_s x Area A B D C x Cos 45° = S_n x 1.414 Area A B D C

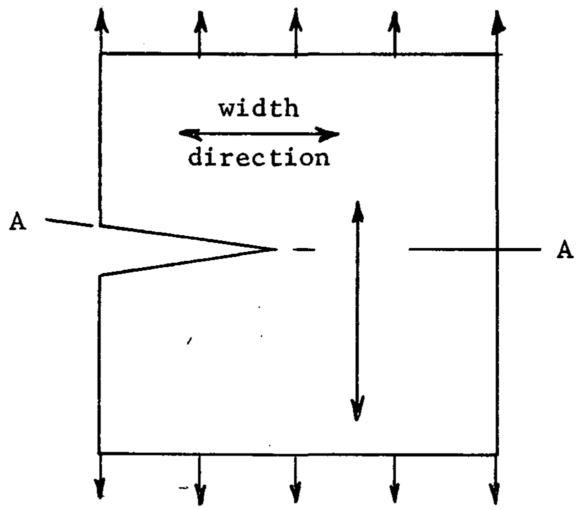
$2\ S_s \times 0.707 = 1.414\ S_n$

$\frac{S_s}{S_n} = 1$

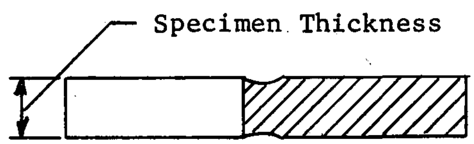
Fig. 2.2 RATIO OF MAXIMUM SHEAR STRESS TO MAXIMUM TENSILE STRESS FOR BAR LOADED IN TORSION which is convenient for testing purposes.

Since brittle fracture usually is initiated at some point of stress concentration, it is generally associated with welded structures, where a welding defect can provide a notch to act as a stress raiser. However, welded structures are by no means the only culprit; any notch can serve as a trigger to brittle fracture by causing the transformation of uniaxial stresses into dangerous triaxial stresses. It should not be thought, however, that this stress raising action in itself is the cause of brittle fracture. Tests on geometrically similar specimens of varying thicknesses show that thin plates are much more resistant to brittle fracture at ordinary temperatures than thicker plates. It is the components of stress in the width and thickness directions that induce brittle behavior. The magnitude of these secondary stresses increases with plate thickness and notch sharpness and depth. The following sketches and discussion which can be found in more detail in E. R. Parker's "Brittle Behavior of Engineering Structures", will show why this is so.

If a uniform load is applied to an unnotched plate, the stress across the plate will be uniform, and the plate will be able to undergo contraction in the width and thickness directions in accordance with Poissons Ratio, since no transverse forces are acting. However, a notch will introduce a stress pattern as shown in Fig. 2.3. Obviously, for a notch of any given geometry, the stress concentration factor will be the same regardless of plate thickness. After very little elongation in the specimen, cracking will occur at the notch



Sketch of Uniformly Loaded Deeply Notched Plate



Section A A
through notch

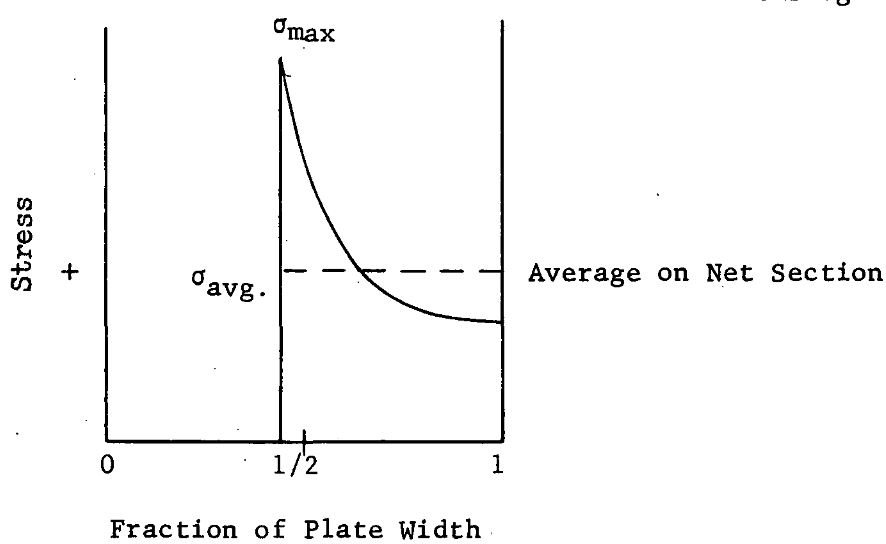


Fig. 2.3 LONGITUDINAL STRESS DISTRIBUTION PRODUCED BY UNIFORMLY DISTRIBUTED LOAD ON A NOTCHED PLATE

apex. After this crack has formed, the presence of the notch is of no further consequence, since the crack destroys geometric similarity. However, by observing the secondary stress distribution in the width and thickness directions, we can see that the stress state becomes more critical for thick plate because of the high tensile stress components that develop in the thickness direction.

Boundary conditions dictate that the stress in the thickness direction must be zero at each face of the plate. Therefore, the stress must have a maximum value which is dependent on plate thickness. Looking at the section through the notched portion of the plate shown in Fig. 2.4, we see that the stress distribution in the thickness direction is as shown. This is due to the fact that the longitudinal stress, being zero across the notch and very high at the notch apex, tends to produce different amounts of lateral contraction in adjacent regions. The highly stressed metal at the notch apex tries to contract, but is restrained by the less heavily stressed portion of metal cut by the notch. The restraint thus causes tensile stresses in the thickness direction at the notch apex. Also, in order to have equilibrium of stresses, the metal cut by the notch will be in compression in the thickness direction.

In the width direction, stresses can be induced by several causes. First, the loading will produce tensile stresses at the notch apex. The second cause of stress in the width direction is due to restraint conditions similar to those discussed before. The stresses in the longitudinal direction drop off very quickly beyond the notch, with the result that there is less tendency for the metal to contract in the width direction as we move away from the notch. Since continuity must be maintained, tensile stresses are set up in the width direction at the notch as shown in Fig. 2.5.

The above description of the triaxial stress pattern which is introduced by the presence of a notch indicates that the condition is much more complicated than a uniaxial condition present without a notch. Although the pattern of these induced stresses may seem fairly straightforward, it should be emphasized that this is true in a qualitative sense only. It may be possible to obtain comparative values for varying conditions of specimen geometry and thickness; however, the quantitative analysis is such a formidable stress problem due to the many variables involved as to be practically out of the question.

Therefore, it is intended in this paper to apply these principles, modifying them as required for conditions of bending, as a means of evaluating those effects of specimen size and geometry on transition temperatures which cannot be attributed to metallurgical differences.

At this point it is perhaps best to define some of the terms which are used in this report. Two primary modes of fractures, namely, shear or cleavage, are of importance in this discussion. Without going into a discussion of the atomic structure of the iron atom, it can be said that shear type fractures are promoted by the action of shear stresses and are actually tears which can be compared

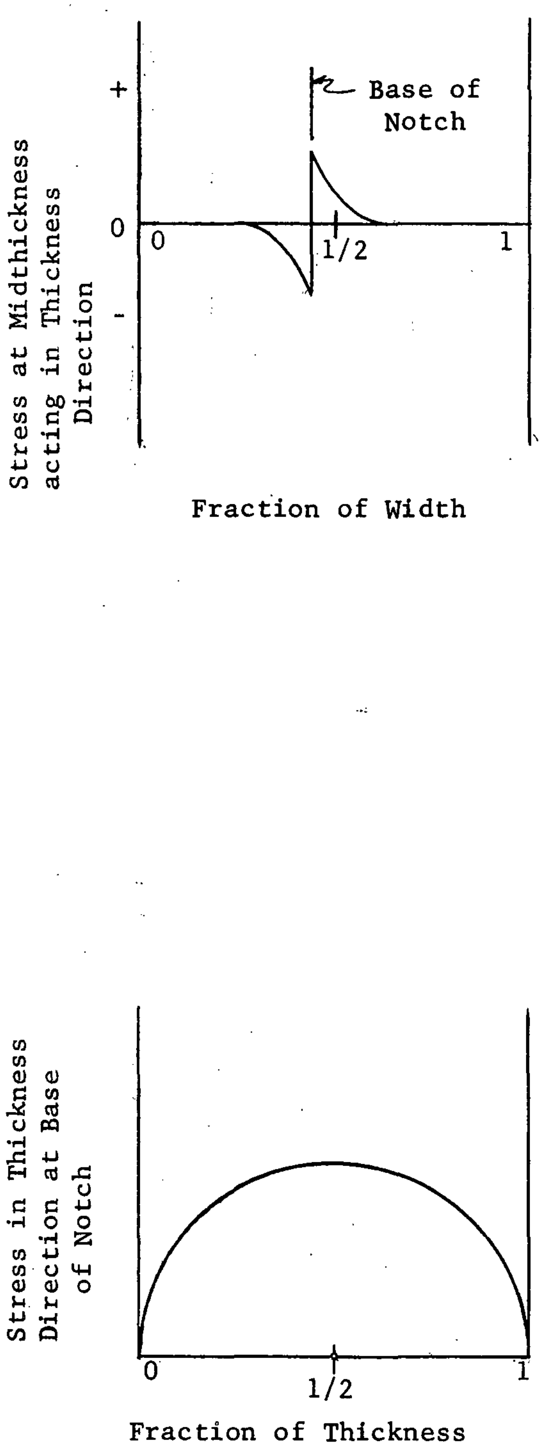


Fig. 2.4 SCHEMATIC DIAGRAM SHOWING DISTRIBUTION OF NORMAL STRESSES IN THICKNESS DIRECTION

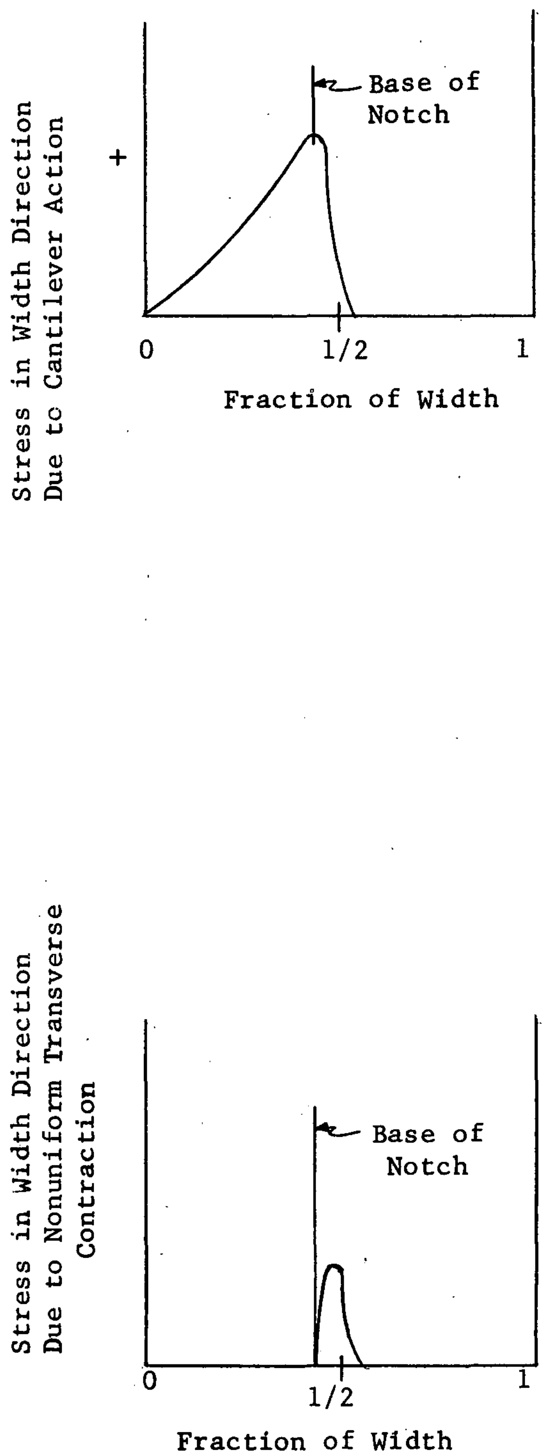


Fig. 2.5 SCHEMATIC DIAGRAM SHOWING DISTRIBUTION OF NORMAL STRESSES IN WIDTH DIRECTION

to the translation of cards in a deck until they are separated into two stacks. The cleavage fracture, however, is caused by normal stresses and is typified by the fracture of mica when the sheets are pulled apart. This fracture normally exhibits a flat surface with a shiny, crystalline appearance, while the shear fracture surface is dull and angular.

The transition temperature may normally be defined as that temperature at which a change from shear fracture to brittle fracture occurs. However, this is a very nebulous definition, since the change usually takes place in a fairly large temperature range. For our discussion then it may be more properly defined as that temperature at which a specified condition, as established by the selection of criteria, will occur.

3. FACTORS AFFECTING BRITTLE FRACTURE

It is obvious from the preceding discussion on the theory of brittle behavior that specimen geometry and thickness have a great deal to do with the temperatures at which brittle behavior will occur based on either a fracture appearance or a ductility criterion. However, there are various other considerations which also contribute substantially to brittle behavior. Four of these considerations which will be discussed briefly are:

A. Rate of loading or strain rate

B. Temperature

C. Presence of residual stresses

D. Notch geometry

In order to better understand the reason for these influences, it may be well to start with a graphic interpretation of the situation as shown in Fig. 3.1. The steel, as mentioned before, will fail in either the cleavage or shear mode. Obviously, the curve which intersects the flow stress curve first will determine the type fracture which will occur. Those factors which tend to alter the brittle behavior will cause the curves to change relative to one another. Also, certain factors will cause the flow curve itself to move. The result is a variety of curves which will indicate the type failure that will occur for the given condition. It should be emphasized that again this is not based on

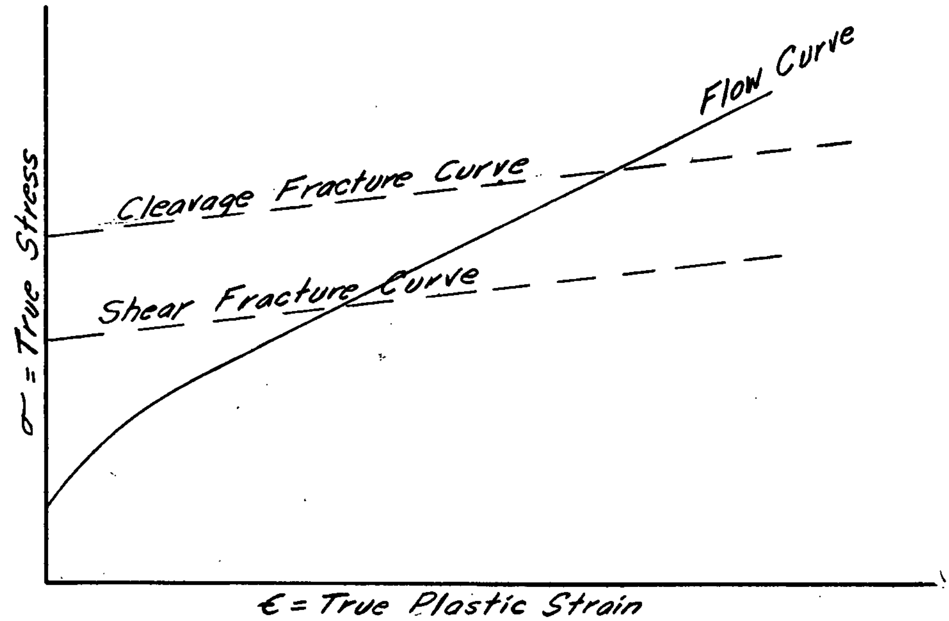


Fig. 3.1 SCHEMATIC REPRESENTATION OF BOTH CLEAVAGE AND SHEAR FRACTURE CURVES INTERSECTING A FLOW STRESS CURVE

empirical data, but is a schematic representation which helps put the variables in the proper perspective.

3.1 INFLUENCE OF STRAIN RATE

It can easily be shown by performing tensile tests on an un-notched specimen at various loading rates that the faster the specimen is loaded, the higher the stress will become before yielding begins. This is understandable when we realize that plastic flow requires time to initiate. In a notched specimen this effect is greatly magnified, since the true strain rate at the notch apex would be the strain rate for an unnotched specimen multiplied by the stress concentration factor.

Thus, other factors being equal, the increase in tensile stress before plastic flow actually starts will tend to change the mode of fracture from shear to cleavage, since shear failure is a consequence of plastic flow. However, the tremendous increase in strain rate necessary to produce a significant effect on the actual flow stress - fracture stress relationship generally makes this an academic rather than a practical consideration.

3.2 TEMPERATURE INFLUENCE

By far the most spectacular effect on brittle fracture is brought about by temperature variation. As can be seen from the curve in Fig. 3.2, a very appreciable reduction in the yield stress occurs with an increase in temperature.

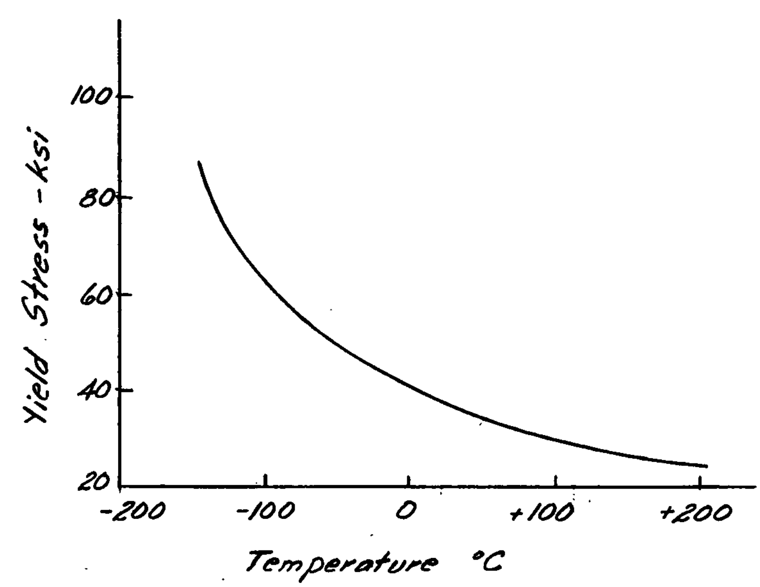


Fig. 3.2 EFFECT OF TEMPERATURE ON YIELD STRESS OF SHIP PLATE

The point should again be brought out that by notching, we bring the temperature at which a more significant reduction in yield stress occurs up into a more convenient range for testing purposes.

3.3 EFFECT OF RESIDUAL STRESSES

The question as to the effects which residual stresses have on brittle fractures is not only unexplained, but is the subject of much heated controversy. Naturally, the question arises mostly with welded structures, where excessive heat in a localized area and the subsequent uneven cooling are capable of producing streses which are of great magnitude. It may be argued that the tendency for plastic flow to occur as a result of these stresses will help to relieve them, and tests have borne out this reasoning. However, these tests were conducted under conditions favoring plastic flow, whereas residual stresses could be expected to contribute to failure only when testing conditions would favor brittle fracture. A really satisfactory test has not been devised. Indications are that a larger size specimen, since it will tend to crack rather than flow plastically, will tend to fail more quickly due to residual stresses.

Investigations have been made on a large number of service failures which give almost indisputable evidence that residual stresses, along with defects in fabrication, caused failures. In some cases there was a condition of zero external loading. Since these two opposing views both appear to be justifiable to a large extent, and since no truly critical test has yet been devised to solve the problem, it seems advisable to do everything possible to minimize these stresses during fabrication until more conclusive evidence is obtained.

3.4 EFFECT OF NOTCH GEOMETRY

The effect of notch geometry on the transition temperature has been the subject of rather extensive study. However, due to the size and complexity of the studies involved, only general comments will be made.

As a notch is made sharper and deeper, the strains become more localized and strain rates are higher for a given deflection rate. Also, by considering the discussion of triaxial stresses, we can see that the degree of triaxiality is increased with sharper notches. All these factors favor a higher ductility transition temperature. However, since the fracture appearance transition is governed by a crack which has formed at the base of the notch rather than by the notch itself, we would expect that the fracture appearance transition would be rather insensitive to notch geometry. This has been borne out by many tests which have shown that specimens with different sizes and shapes of notches may have widely varying ductility transitions with little change in fracture appearance transition temperature.

4. DESCRIPTION OF THE EXPERIMENTAL PROGRAM

The test program as originally set up consisted of the three following types of brittle fracture tests.

A. Van der Veen tests

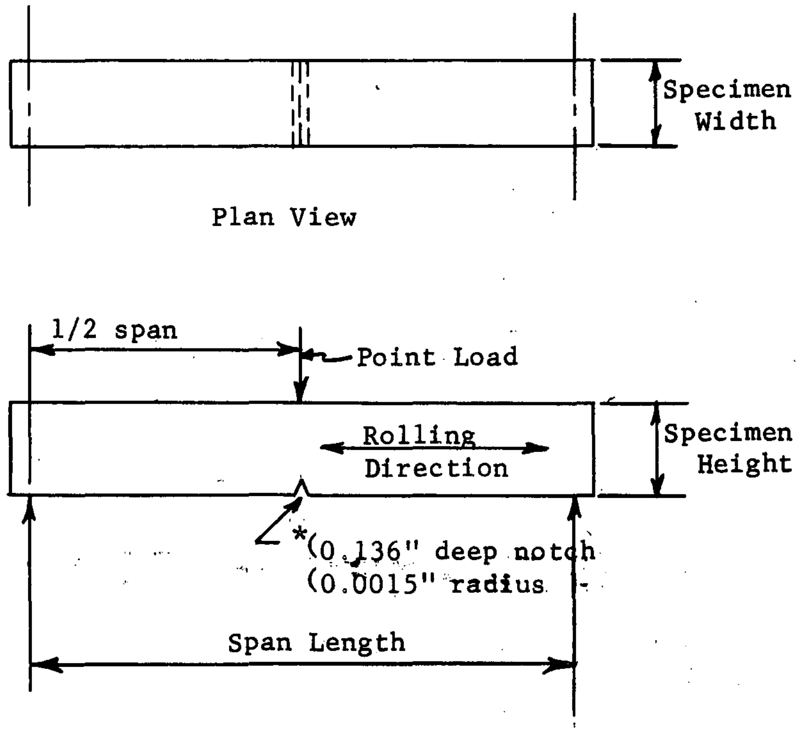
B. Bagsar tests

C. Drop weight tests

All tests were conducted using ABS Class C (normalized) ship plate steel. However, at the second meeting of the Ship Steel Committee the suggestion was made, and promptly adopted, that high strength United States Steel Corporation's "T-1" steel would be supplied for a similar set of tests. These tests will be conducted at a later date.

4.1 VAN DER VEEN TEST SPECIMENS

The Van der Veen test consists essentially of applying a concentrated load at the midpoint of a notched beam, so placed that the load will fall directly above the notch, thus putting the notched side in tension, as shown in Fig. 4.1.



Test Nomenclature: Width = Plate Thickness

Standard Height = 2.76"

1/2 Standard Height = 1.38"

1/4 Standard Height = 0.69"

Standard Span = 9.5"

Long Span = 16.5"

* Similar for all Van der Ven Specimens

Fig. 4.1 VAN DER VEEN TEST SPECIMENS

Each complete Van der Veen series consisted of approximately fifteen test specimens. The pertinent dimensions for each series is given in Table IV.1.

TABLE IV.1 VAN DER VEEN TEST SPECIMENS

Specimen Width (inch)	Specimen Height	Specimen Span
1, 2, 3	standard	standard
1, 2, 3	1/2 standard	standard
1, 2, 3	1/4 standard	standard
1, 2, 3	standard	long
1*, 2*	standard	standard
3/4, 1-1/2	standard	standard
3/4, 1-1/2	1/2 standard	standard
3/4, 1-1/2	1/4 standard	standard

*These specimens were split from 3" thick plate to compare the metallurgical effects on transition temperature of these plates with the 1" and 2" plates as rolled.

All specimens were cut from the plate with the longtiudinal axis in the direction of rolling so that the notch was perpendicular to the rolling direction of the plate. This relation between notch direction and rolling direction was maintained in all tests, including the Charpy specimens. As a matter of interest, mention should also be made of a series of one inch thick standard height and span specimens which were tested with the notch parallel to the rolling direction. These exhibited significantly higher transition temperature and lower maximum load than the one inch thick plate tests conducted in the conventional manner.

The notch itself was 0.136 inches deep with a radius of 0.0015 inches. It was pressed to the required depth using a hardened steel die, and the depth was regulated by a dial gage mounted on the movable head of the testing machine which was being used to press the notch. After notching, the specimens were filed on both sides of the notch to obtain a smooth surface for the purpose of making measurements of lateral dimensions before and after testing in order to find the percent lateral contraction.

The original testing program called for tests to be performed on 1", 2" and 3" thick plates at the various heights and spans that are shown in Table IV.1. At a later date, it was decided that advantageous information could be gained by running additional series of tests on three-quarter inch plate and one and one-half inch plate thicknesses of the same heat of ABS normalized steel used on the previous Van der Veen tests. This is the only reason for the separation of the original plate thicknesses from the 3/4" and 1-1/2" thicknesses in Table IV.1. The complate results for all thicknesses along with copies of the original data are given in the Appendix.

4.2 BAGSAR TEST SPECIMENS

The geometry of the Bagsar test specimen is as shown in Figs. 4.2 through 4.5. The primary difference between this test and the Van der Veen test is that in this type test an eccentric loading condition is produced by the off-center loading points, thus creating a combined

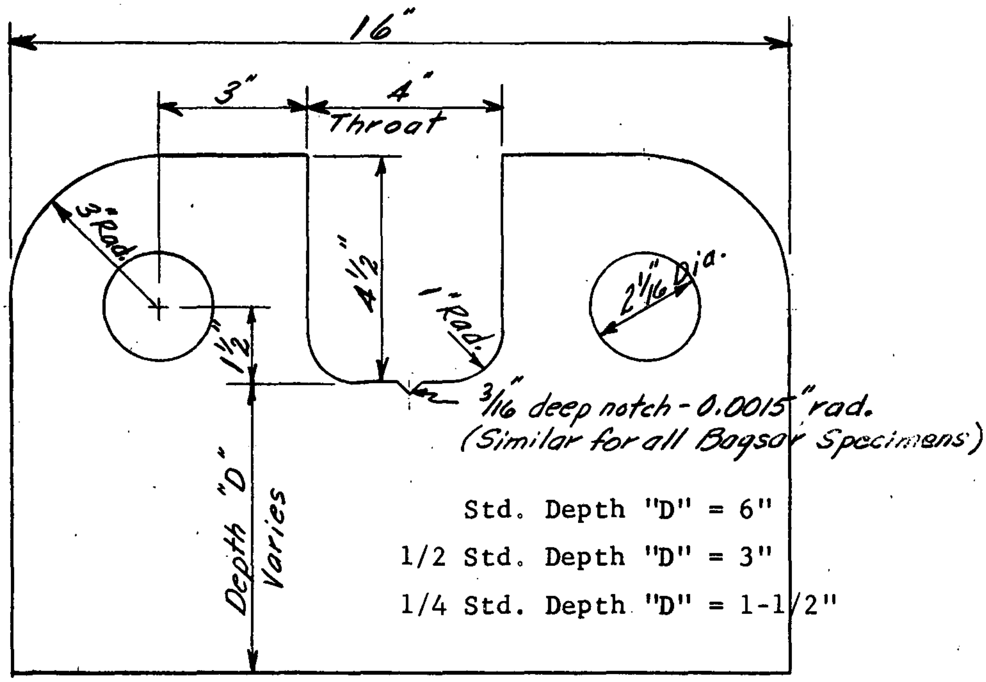


Fig. 4.2 STANDARD THROAT WIDTH BAGSAR TEST SPECIMEN FOR 1-INCH AND 2-INCH THICK PLATE

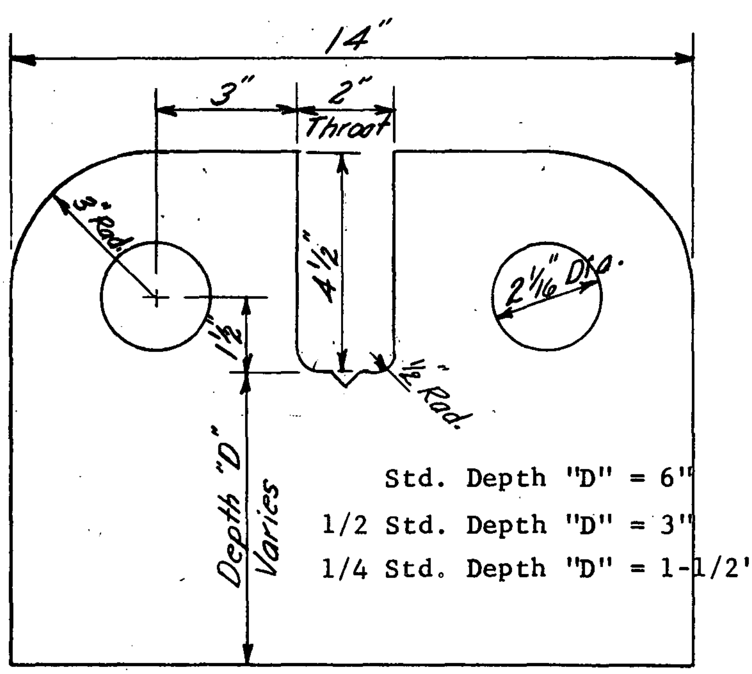


Fig. 4.3 NARROW THROAT WIDTH BAGSAR TEST SPECIMEN FOR 1-INCH AND 2-INCH THICK PLATE

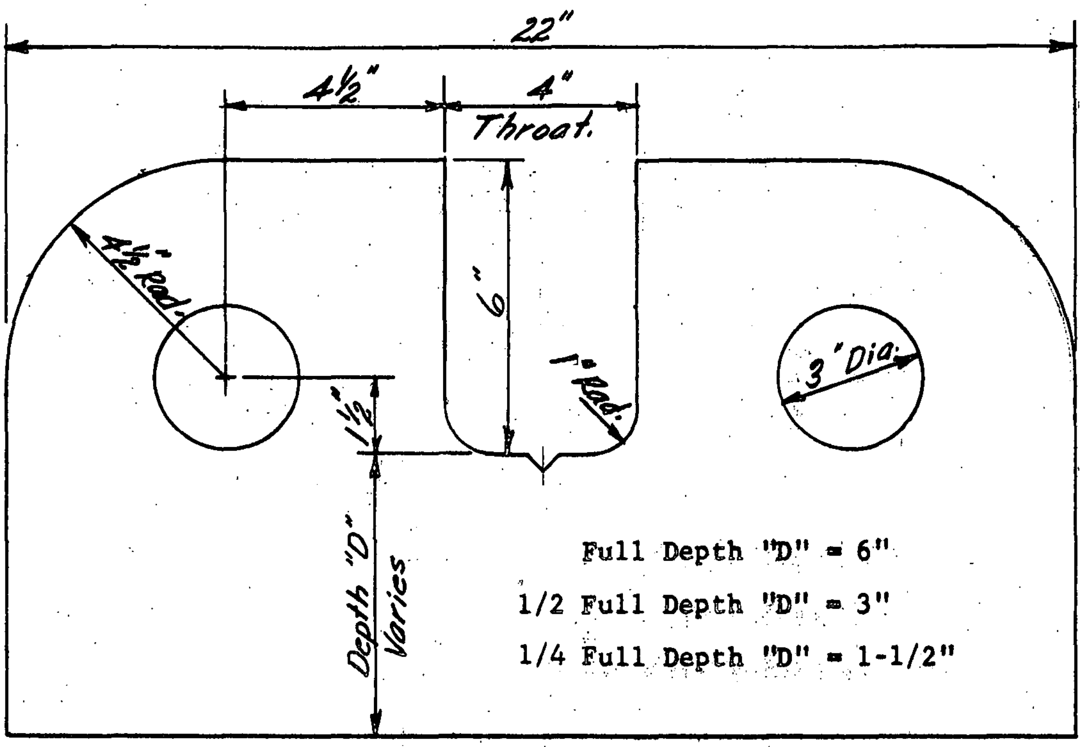


Fig. 4.4 STANDARD THROAT WIDTH BAGSAR TEST SPECIMEN FOR 3-INCH THICK PLATE

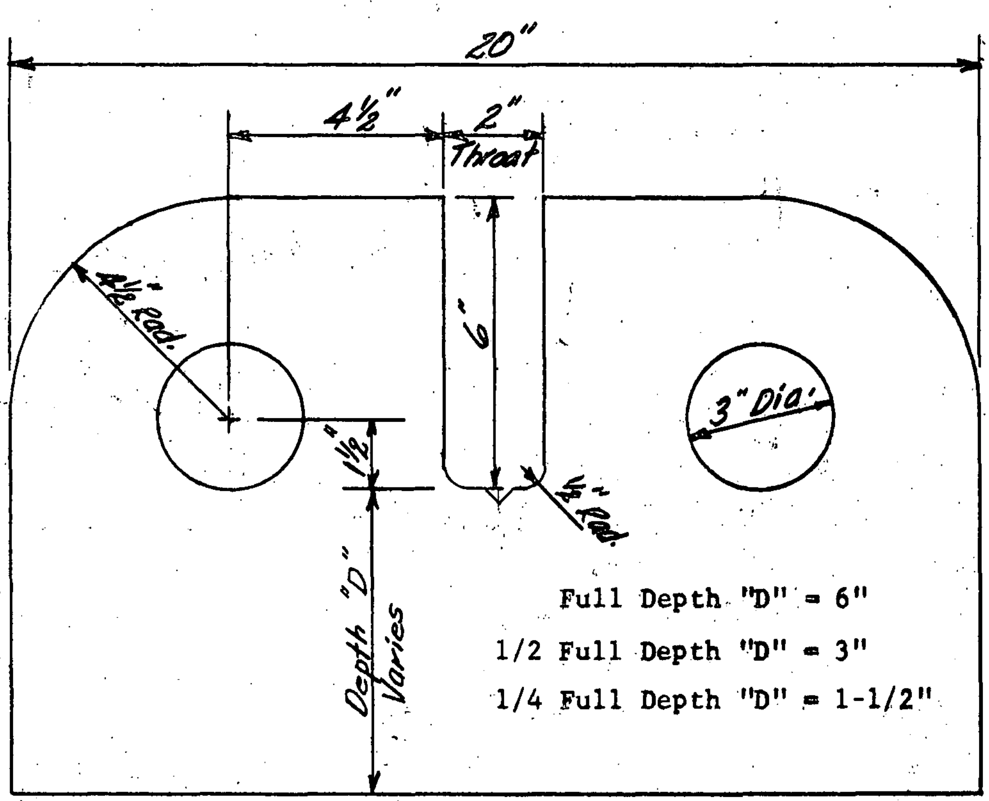


Fig. 4.5 NARROW THROAT WIDTH BAGSAR TEST SPECIMEN FOR 3-INCH THICK PLATE

condition of tensile and bending stresses at the notch apex. An advantage of this geometry is that by proper selection of load and eccentricity, compressive stresses throughout the section can be eliminated. This is desirable because it provides a more favorable condition for crack propogation. It is obvious that if compressive stresses were high enough, a cleavage crack would not be able to propagate through the zone. It is generally accepted that the initiation of the crack should be essentially the same for bending alone as for tension plus bending. However, greater stress gradients do occur in bending alone, which result in higher secondary tensile stresses, and thus a greater tendency for crack initiation to occur at the notch. Although it is true that the geometry of the Bagsar specimens used in these tests did not allow for elimination of compressive stresses, it nevertheless helped to reduce them to values below those of the Van der Veen stresses for a similar size specimen.

Again, the notch was pressed into the specimen using the same procedure as was described for the Van der Veen specimens. However, in this case the die was pressed into its full three-sixteenths inch depth. The radius was again 0.0015 inches. After notching was completed, the sides of the specimens were again filed to obtain a smooth surface for making measurements of lateral dimensions before and after testing.

Mr. A. B. Bagsar, who originated these tests, selected the specimen shape on the basis of ease of preparation and because he felt the stress conditions approached those of ship steel in service.

A total of one hundred and twenty of these specimens were tested, representing twelve complete series of ten specimens each. The variation in size and geometry of these specimens is tabulated in Table IV.2.

TABLE IV.2 BAGSAR TEST SPECIMENS

Specimen Thickness (inch)	Specimen Depth	Throat Width	Number of Specimens
1, 2, 3	standard	standard	10 each
1, 2, 3	1/2 standard	standard	10 each
1, 2, 3	1/4 standard	standard	10 each
1, 2, 3	standard	narrow	10 each

The complete results of the Bagsar Tests are shown in the Appendix.

4.3 DROP WEIGHT TESTS

The third type of tests to be investigated in the project was the drop weight test. As of the writing of this paper, the testing has not been undertaken on these specimens. The geometry of the specimens involved will be for the most part the same as was used for the Van der Veen specimens. However, the loading will be of the impact type, with stops used to prevent excessive deflections in the specimens.

4.4 CHARPY TESTS

In addition to the three types of tests mentioned above, additional data was obtained in the form of standard V-notch Charpy Tests. Approximately 12 specimens were cut from random points throughout the thickness of each of the one, two and three inch plates used for both the Van der

Veen and the Bagsar tests, as well as from the three-quarter and one and one-half inch plates used for the later Van der Veen tests. The primary purpose of obtaining this information was to evaluate the effect of varying metallurgy in the various thicknesses. After plotting the energy curves, the values of the ductility transition temperatures based on fifteen foot-pounds of energy were taken for each thickness, and the difference was applied to those values for transition temperature found in the Van der Veen and Bagsar tests as a correction for metallurgical differences. The tabular values of transition temperatures as given in the Appendix contain this correction factor. Therefore, further comparisons of the values obtained can be made on the basis of considerations of specimen geometry and size effects without considering metallurgical variations. This procedure assumes that it is justifiable to apply the correction based on the fifteen foot-pounds of energy value to both the fracture appearance and ductility criteria. Although this practice may be a debatable subject, the evidence furnished by comparing the transition temperatures of the 1" and 2" plates as-rolled with the 1" and 2" plates which were split from 3" plate indicates that the correction for some reason yields much better comparisons for the fracture appearance criteria than for the ductility criteria. This may be further evidence to be considered in the later discussion concerning the difficulty in obtaining consistency in ductility transition temperature measurements.

A clarifying statement should be made as to the selection of the fifteen foot-pound ductility criteria as the basis of this correction. This was not a random low energy selection, but was a value associated with actual tests run on steel which was removed from plates that had actually experienced service failures. In the cases where Charpy tests were run on these steels, it has been found that the impact energy level was ten to fifteen foot-pounds at the temperature where failure actually occurred. The resulting temperatures obtained for fifteen foot-pounds of energy for the various thicknesses, and the corrections made to the plates are given in Table IV.3 below.

TABLE IV.3 CHARPY V-NOTCH RESULTS (Van der Veen Test Plate)

Plate Thickness (inch)	15 ft.-lb. Transition Temperature ($^{\circ}$ F)	Temperature Correction to Plate
1	- 60	+ 15° Added
2	- 45	None
3	- 50	None
3/4	- 50	Results Uncorrected
1-1/2	+ 15	Results Uncorrected

(Bagsar Test Plate)

Plate Thickness (inch)	15 ft.-lb. Transition Temperature ($^{\circ}$ F)	Temperature Correction to Plate
1	- 65	+ 20° Added
2	- 40	None
3	- 45	None

5. TEST APPARATUS AND EXPERIMENTAL PROCEDURES

5.1 VAN DER VEEN TESTS

The Van der Veen tests for each series were performed at varying temperatures in order to obtain the transition temperatures for the selected criteria. The specimens were cooled to a given temperature in a bath of alcohol and dry ice. Temperature was held constant for a sufficient time to allow for uniform cooling through the specimen thickness. The specimen was then removed from the bath and as quickly as possible placed on roller supports in the lower table of the 300 kip universal hydraulic testing machine. The specimen was aligned horizontally with the loading device in the upper head, and the head was run down electrically until the loading device just touched the specimen at its centerline. Testing was completed by opening the loading valve its full amount, which was established beforehand to cause a head movement of approximately one inch per minute. Deflection readings were taken from the moving head using dial gages. By carefully eliminating all unnecessary time consuming operations in the placement of the specimens before the tests were actually run, the time required for correct placement of the specimen was held to approximately fifteen seconds. This, of course, was desirable to eliminate the possibility of the specimen warming up to any extent.

By plotting values of the depth of shear fracture, or so-called thumbnail distance, as well as lateral contraction at the root of the notch after each test was performed, it was possible to pick the testing temperatures which would give the required information. It was also necessary in each series of tests to go to a low enough temperature to attain a significant drop in maximum load to cause fracture; this drop in load is a ductility criterion representing complete cleavage fracture with practically no lateral contraction at the base of the notch.

5.2 BAGSAR TESTS

The Bagsar tests were conducted with the test specimens immersed (in alcohol and dry ice) at the time of testing, thus eliminating the possibility of the specimens warming up during testing. The entire bath was supported in the lower head of the 800 kip universal screw type testing machine, and the lower part of the Bagsar specimen was pinned to a clevis arrangement in the bottom of the bath as is shown in Fig. 5.1. The top hole of the specimen was then attached to a similar clevis in the upper head of the testing machine. Loading was then applied through the pins, again at a rate of approximately one inch per minute. Plotting of results was again done to help select the proper testing temperatures as the tests continued. Essentially the same criteria were used to evaluate transition temperatures as for both the Bagsar and Van der Veen specimens, except for a minor change in the constant shear (fracture appearance) value. Difficulty was encountered in measuring the widening of the throat as loading progresses, since the entire throat was immersed at cold temperatures. Therefore, these measurements were discontinued.

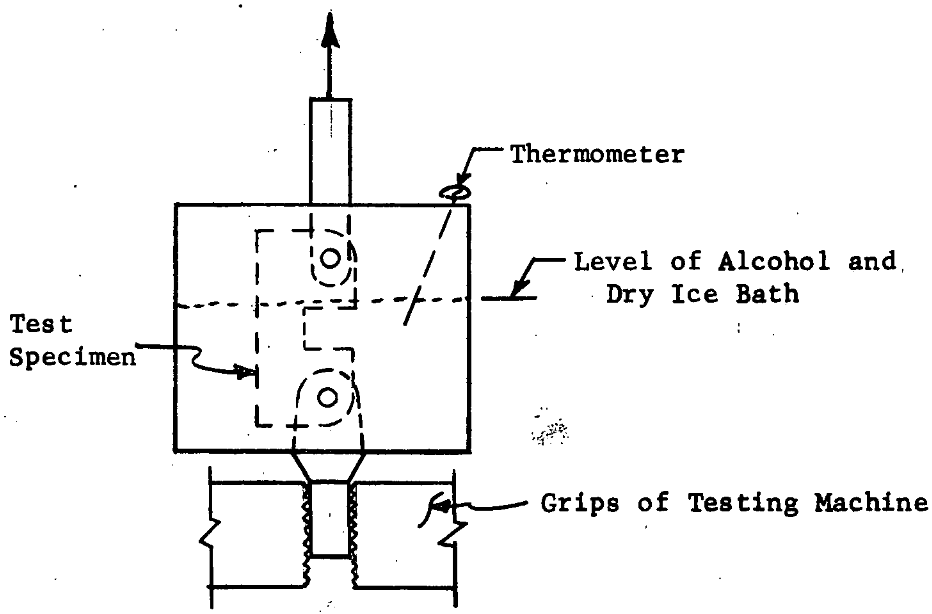


Fig. 5.1 BAGSAR TEST SETUP IN 800,000 lb. UNIVERSAL SCREW TYPE TESTING MACHINE

5.3 GENERAL CONSIDERATIONS

In order to make certain that several factors which could significantly effect the test results did not occur, certain other tests were made. The cooling time required in order to be sure that a uniform temperature existed throughout the specimen at the time of testing was ascertained by drilling a hole to mid-depth of the thickest plate and inserting a thermocouple. The hole was then sealed and the specimen placed in a bath. Readings of temperature of the specimen vs. time in the bath were taken. This was done for bath temperatures of minus thirty degrees F. and minus seventy-five degrees F. The curves, shown in Fig. 8.1

of the Appendix, indicated that fifteen to twenty minutes cooling time for the larger thicknesses was entirely ample. This test also indicated that if the specimen was accidentally cooled below test temperature, it would be best to test another specimen in its place, since a much greater time is required for warming it back up to test temperature. Another procedural check was made on notch radius variation due to dulling of the notching die. Ten notches were pressed into a plate with an initially sharp die and the variation in radius was checked under a microscope to determine if any appreciable dulling of the notch occurred. Upon measuring the radii by using a tool maker's microscope, it was found that practically no deviation ($\pm$ 0.0001") from the ideal 0.0015 inch radius existed.

6. THEORETICAL DISCUSSION OF TRANSITION TEMPERATURES

6.1 INTRODUCTORY REMARKS

The evaluation and interpretation of data accumulated from the Van der Veen and Bagsar tests is a rather difficult task. The wide amount of scatter which is inherently present in tests of this type makes the selection of the transition temperature a problem, since in practically all criteria a variation of ten to fifteen degrees F. can easily be gotten, depending on the judgment of the person who is interpreting the data. This is a most important fact to keep in mind when trying to establish definite trends, since a small variation in an unexpected direction can make the theoretical reasoning appear to be erroneous.

The establishment of transition temperature for brittle fracture depends mainly on two classes of accepted criteria, namely, ductility criteria and fracture appearance criteria. The ductility criteria are based on the occurrence of a given amount of plastic flow at the root of the notch prior to fracture. The fracture appearance has to do with the crack propagation through the specimen, and the appearance of the fracture as it changes from shear to cleavage. After a crack has started, it is essentially a very sharp notch which replaces the existing notch. Therefore, the fracture appearance transition temperature is much less dependent on notch geometry than is the ductility transition temperature. On the basis of these two classes a list of the criteria selected for evaluating both the Van der Veen and the Bagsar tests is given below.

FRACTURE APPEARANCE CRITERIA

Van der Veen Test

1. 50% Shear Depth
2. 8 mm. Shear Depth

Bagsar Test

1. 50% Shear Depth
2. 0.75 in. Shear Depth

DUCTILITY CRITERIA

Van der Veen Test

1. 2% Lateral Contraction at root of notch
2. 0.06 in. Lateral Contraction at root of notch
3. 1/2 the Deflection at maximum ductile load
4. Drop in maximum load

Bagsar Test

Same criteria as for Van der Veen tests except that 1/2 the deflection at maximum ductile load was omitted

6.2 DISCUSSION OF VAN DER VEEN TEST RESULTS

A. Fracture Appearance Criteria

Various investigations have shown that on tensile brittle fracture tests the thickness of the specimen has an effect on the fracture appearance transition temperature, while the width of the specimen does not have any appreciable effect. This is understandable in view of the fact that a more or less constant stress condition exists over the width of the plate. However, in the case of Van der Veen or Bagsar tests, where bending occurs which causes a stress variation across the depth of the specimen, some size effects could be expected. An investigation of the fracture appearance transition temperature criteria for both fifty percent shear failure and eight millimeter (8 mm.) shear failure shows this to be the case.

The results for these criteria indicate that the fracture appearance transition temperature tends to increase with increasing thickness and increasing depth for a given thickness. In order to establish the reason for the temperature increase as the plate thickness increases, we need only consider the previous discussion on triaxiality and the increased stresses in the thickness direction due to additional lateral restraint. However, it is another matter to try to establish the effect of specimen height on the fracture appearance transition.

In Griffith's theory of fracture of brittle solids, he obtains the formula

$$\sigma \approx \frac{Ew}{C}$$

where E = Modulus of Elasticity

w = Surface Energy per Unit of Area

C = Diameter of Internal Crack or Twice the Length of a surface crack

and σ = Stress required to make a crack grow

By this theory it can be seen that the stress required to make a crack grow is inversely proportional to the square root of the crack length. However, Orowan pointed out that the above equation does not hold for steel because of its property of ductility. The plastic strain energy associated with fracturing is on the order of one thousand times the surface energy. Therefore, he modified the equation as given below to include the plastic strain energy term "p".

$$\sigma \approx \frac{E\ (w + p)}{C}$$

In order to help understand the transition temperature variations which occurred, it becomes necessary to attempt to get an idea of the relative stresses which exist in the various depth sections at the time when failure actually occurs. In order to accomplish this, a plot was made of actual breaking load vs. percent cleavage area, for a given series, with the three depths for any thickness superimposed onto one graph. After plotting the curves for a given thickness, a comparison of the breaking loads at each depth was made at the fifty percent shear value. The values were compared and the relative stresses were found to be as indicated on the plots in Fig. 8.2 through Fig. 8.4. Similar plots were made for the varying thickness's of a given depth to help explain the variation in this direction also, as indicated in Fig. 8.5 through Fig. 8.7 these plots, using actual breaking loads, were based on the assumption that for the actual stressed area at the time of brittle fracture, the formula given below would be valid.

$$\sigma_{BR} = \frac{P_{BR}\,L}{4} \times \frac{C_{CL}}{I_{CL}}$$

where σ_{BR} = Breaking stress at the base of the shear crack

P_{BR} = Observed breaking load

L = Span length

C_{CL} = Cleavage depth $\div 2$

Since breaking load varies directly as the stress in this case, it was used as the basis for comparison rather than the stress itself. Again, it should be emphasized that these stresses are relative, since variations such as the curved beam and notch (crack) stress concentration factors are unknown, but considered to be more or less constants.

The comparative stress levels in various depths may be evaluated for the eight millimeter (8mm.) shear depth criteria in the same manner; however, since this represents a different percentage of cleavage area for each depth, the comparison is complicated by the fact that in some cases this shear depth actually is a very small percentage of the total depth. The breaking load then is beyond its maximum point and is dropping, as shown in Fig. 8.2.

An idea of the comparative stress values can still be obtained, however.

After getting these relative stress levels, it is now possible to return to Orowan's formula with the realization that by selecting a given fracture appearance criteria, we are actually forcing a relative stress level to occur. These comparative levels, then, will show in which direction "p" must vary in order to obtain these comparative stresses. The important point to consider here is that "p" is a term which is temperature dependent. If the temperature is above the transition point "p" is large; thus the stress required for crack propagation will be large. However, if the temperature is below the transition range, "p" will be small and brittle fracture is more apt to occur. In fact, we see that at a given stress level we can cause brittle failure to occur just by lowering the temperature and thus "p".

It must be kept in mind that when comparing the fifty percent shear criteria for various depths, the crack length at the point where brittle fracture occurs will vary, whereas this factor will remain constant for a criteria governed by a specific value i.e. eight millimeter (8 mm.) shear. Thus, if we are able to force a fifty percent brittle fracture condition to occur at the condition of lower stress which exists in a shallower depth specimen, then "p" must be substantially less in a specimen of lesser depth. It follows then that if "p" is less the transition for fracture appearance should occur at a lower temperature for the shallower depth. By the same reasoning, the fracture appearance for a constant amount of shear, again taking into account the lesser stress in the shallower depth specimens, would cause a lower transition temperature, although there should be less variation because of the constant crack length. The smaller variation of eight millimeter (8 mm.) shear transition temperatures with specimen depth seem to bear out this reasoning.

Mention should be made of the apparent inconsistency of the three-quarter inch plate transition temperatures for fracture appearance. This variation was found also in a large number of tests run at Lehigh University by S. A. Agnew while working on his doctoral dissertation. It was concluded that the effect was due to cold working which occurred in these thin specimens and resulted in an embrittling effect, especially in the shallower depths where excessive deflection occurred even when the specimen was exhibiting most cleavage fracture.

The discussion of the relative stress values for the varying depths and thicknesses can be carried one step further. It can be seen from the curves of breaking load vs. percent cleavage area that these relative stress values hold fairly constant for the depth variation in each thickness, as well as for the thickness variations for a given depth. These values are given in Table VI.1.

TABLE VI.1 RELATIVE STRESS LEVELS FOR VAN DER VEEN SPECIMEN GEOMETRY VARIATIONS

Specimen Depth	Average Relative Stress Values for 1", 2" and 3" Thicknesses
full	1.00
1/2 full	0.80
1/4 full	0.69

Specimen Thickness	Average Relative Stress Values for Full, Half and Quarter Depths
1 inch	0.75
2 inch	0.92
3 inch	1.00

After the plots were made, an attempt was made to establish a mathematical expression for the curves through the experimental points. For the stress level variations with depth, the curve

$$Y = A\left(1 - \frac{1}{e^{X}}\right) \qquad \text{where } X = \text{depth in inches}$$
$$Y = \text{relative stress value}$$

was selected. Values of X and Y were substituted in the equation, and the value of $A = 1.07$ was found to give a satisfactory curve. Although the curve deviates from the experimental point at 1/4 full depth, it fits the other points well. The curve also appears to be justified by the boundary conditions that as depth approaches zero, the relative stress value also approaches zero and when depth approaches infinity the relative stress level brought about by lateral restraint will approach a limiting value. This limiting value of depth was found to be at approximately six inches by assigning values to X and checking the variation of Y. It can also be noted at this point that Bagsar, in his investigations, also obtained a value of six inches as the depth at which the breaking stress becomes independent of further increases in specimen depth.

A similar attempt was made to find an expression for the relative stress variation with plate thickness. Here the curve

$$Y = A \tanh x \qquad \text{where } X = \text{plate thickness}$$
$$Y = \text{relative stress values}$$

was found to more readily fit the experimental points, as well as the boundary conditions mentioned above. Substitution of the experimental values led to the selection of A = 1.00. Substitution of increasing values of X indicated that the limiting restraint in this direction will be approached as the plate thickness approaches four inches. Both limiting values are shown by the theoretical curves drawn on the plots in Fig. 8.8 and Fig. 8.9.

B. Lateral Contraction Criteria

The ductility transition temperatures are based on several different criteria, as indicated on page 31.

Turning to the lateral contraction criteria, it becomes necessary to deal with the contraction associated with plastic flow at the notch root prior to crack formation, rather than the variation in stress conditions as the crack propagates. In considering these criteria, a few general statements must be made concerning their value. In using the constant amount of lateral contraction, i.e. 0.06 inches, sizeable variations in transition temperature were encountered which did not seem to conform to any pattern. Naturally, this constant amount corresponded to six percent lateral contraction in the one inch thick specimen, two percent lateral contraction in the three inch thick specimen, etc. What this difference in percent contraction essentially causes is a more or less invalid comparison, since these amounts occur in entirely separate portions of the transition curve. The transition temperature would occur in that region normally classified as the low energy region for the three inch thick specimens, whereas it would occur in the high energy level for the one inch specimens. Indeed, in some cases it may be nearly impossible to obtain six percent lateral contraction for a given steel plate.

Therefore, the constant percentage of lateral contraction would appear to lend itself as a more valuable criterion, since it allows comparisons for all thicknesses in the same general region of the transition curve. The results indicate that transition temperature values based on this criterion will increase with both increasing thickness and decreasing depth in a given thickness.

In first considering the effect of plate thickness on ductility transition temperatures, it is evident that a thicker plate will not contract laterally a given amount as readily as a thin plate because of the restraint involved. Thus, a higher transition temperature would result. As far as specimen depth is concerned, for a condition of bending or bending plus tension a steeper stress gradient will exist across the shallower sections which would tend to promote brittle fracture at a higher temperature. Thus, it would seem that a general statement could be made that the ductility transition temperature would rise with an increase in specimen thickness and lower with an increase in specimen depth for a given thickness. However, from the test results obtained it does not appear that a simple relationship exists, but possibly a more complex one involving the ratio of specimen thickness to height. It would appear that if a plot of thickness, height ratio versus transition temperature at two percent lateral contraction were made, the temperature would rise perceptibly near the ratio of one, i.e., a square section, and would lower on either side of this ratio. If this is so, it could be explained by the assumption that in a practically square section the normal stresses due to restraint would tend to become more equal, with the result that shear failure (and lateral contraction) will be less apt to occur. However, this is only an assumption since not enough points are available to insure that the transition temperature actually varies in this way.

The lateral contraction results were rather disappointing from the standpoint of obtaining useful relationship based on geometry. The investigators experienced difficulty in obtaining accurate lateral contraction measurements at the notch root because of the varying types of fracture which occurred. In regard to this, mention should be made of the notation called "cup fracture" at various points on the data sheets. This type fracture, which occurred more often in the thicker sections but was evident in all series, was characterized by two shear lips, both occurring on the same broken half of a specimen to form a cup shaped fracture. This type of fracture occurred in no observable temperature pattern whatsoever, and always showed a larger amount of lateral contraction than specimens which did not break in this manner. Naturally, when plotted, these results would tend to influence the final selection of the transition temperature. This is but one example of the problem encountered in making the basic but vital measurements of contraction. The author of this paper can make no useful suggestions at this time concerning a more foolproof method of measuring lateral contraction; however, it may be possible to make this measurement at a selected point some distance away from the notch root so that the type failure will not influence an accurate lateral contraction measurement. In an investigation of this sort it is very essential and helpful to have a criterion which is quite sensitive to variations of geometry, as are the ductility criteria. However, if this is to be the case it would seem that it would be desirable to eliminate all possible scatter producing factors which may affect the selection of transition temperature more than the geometry itself.

C. Deflection Criterion

The ductility criterion for one-half the deflection at maximum load was arbitrarily picked by the investigators without knowing that it was also originally used as a criterion by Van der Veen himself. It agrees fairly well with the two percent lateral contraction criterion. Upon looking at the data it can be seen that the deflection at maximum load is fairly constant as long as there is no substantial drop in maximum load. The agreement between the transition temperatures for the two criteria, rather than having a structural significance, appears due to the fact that by chance, the two criteria occur at approximately the same energy level in the transition curve. An advantage exists in the criterion for one-half the deflection at maximum load because in the tests considered, it gave more definite points for the selection of the transition temperature - the lateral contraction criterion showed appreciably more scatter.

D. Drop in Maximum Load Criterion

The drop in maximum load should also be mentioned as another ductility criterion. A very significant and well defined drop will occur when a low enough temperature prevents any appreciable lateral contraction at the base of the notch. The transition temperatures for this criterion were selected as the point at which a drop occurred with no scatter (in the form of higher loads) at lower temperatures. However, this too poses a problem, since the appreciable scatter observed in the amount of lateral contraction automatically will be accompanied by scatter in maximum load if a specimen unexpectedly exhibits a fully cleavage type of fracture.

6.3 DISCUSSION OF BAGSAR TEST RESULTS

The Bagsar tests, as stated before, were evaluated using nearly the same criteria as were used for the Van der Veen tests. The fracture appearance transitions were again checked using relative stress levels found by plotting breaking load vs. percent cleavage area and using the formula

$$\sigma_{Br} = \frac{P_{BR}}{A_{CL}} + \frac{P_{BR}\, E_{CL}\, C_{CL}}{I_{CL}} \qquad \text{Where } E_{CL} = 1.5'' + \text{shear depth} + \frac{+\, d - \text{shear depth}}{2}$$

and the other terms are as before.

However, these plots did not give as smooth curves as did the Van der Veens, since the testing machine which was used did not allow for accurate measurement of actual breaking loads. For this reason these curves were not included in this report.

Mention should be made of the fact that while the three inch thick Bagsar specimens were being made, a number of the specimens were mistakenly flame cut near the notch area. Adjustment was made by machining one-quarter inch from the depth; however, subsequent testing indicated that the heat affected zone had not been completely removed. Therefore, the results of the Bagsar tests given in the Appendix will not include data on the three inch thick plates. The tests will be conducted at a later date if it is decided that further machining of the heat affected zone will not drastically change any of the transition values which would have been obtained with the original specimen depth.

7. SUMMARY AND CONCLUSIONS

The main purpose of this report has been to examine, through experimental data obtained from many tests, the variations (and the reasons for these variations) of transition temperatures with test specimen depth and thickness. It is hoped that some information of practical use has been obtained in the form of "infinite" specimen dimensions. Nevertheless, it is a certainty that not all possible approaches have been explored in attempting to evaluate this data; for this reason it was felt that the inclusion of the original data sheets would assist, and perhaps encourage, others to seek new methods of obtaining useful information, and to supplement any further information which they may gather through additional tests.

It is felt that upon completion of the remaining three inch plate thickness Bagsar tests more useful comparisons can be drawn, not only for the depth and thickness variations as was done for the Van der Veen Tests, but for similar depths and thicknesses which exist between the two types of tests. Perhaps in this way more intelligent selections can be made regarding an ideal test specimen geometry to simulate a given service condition.

Also, as of the final typing of this report, United States Steel Corporation "T-1" steel is being cut into Van der Veen Test specimens.

These tests should not only confirm some of the results discussed in this paper, but will also lend information as to the effect of the physical and metallurgical properties of the various steels on notch toughness.

8. APPENDIX

TABLE VIII.1 FINAL VAN DER VEEN RESULTS OF TRANSITION TEMPERATURES (°F.)

TEST SPECIMEN			FRACT. APPEAR. CRITERIA		DUCTILITY CRITERIA			
Plate Thickness (in.)	Depth (in.)	Span (in.)	50% Shear	8 mm. Shear	2% Lateral Contraction	0.06" Lateral Contraction	1/2 Defl. at Max. Ductile Load	Drop in Max. Load.
≠ 1	2.76	9.5	- 10	- 60	- 70	- 60	- 70	- 70
1	1.38	9.5	- 30	- 30	- 35	- 35	- 35	below - 100
1	0.69	9.5	- 60	- 60	- 60	- 45	- 70	below - 100
1	2.76	16.5	- 40	- 55	- 75	- 55	- 70	- 80
2	2.76	9.5	+ 5	- 20	- 50	- 35	- 35	- 35
2	1.38	9.5	- 10	- 20	- 30	- 45	- 30	- 40
2	0.69	9.5	- 25	- 25	- 30	- 30	- 30	- 30
2	2.76	16.5	+ 15	- 20	- 45	- 30	- 50	- 50
3	2.76	9.5	+ 15	0	- 15	- 15	- 15	- 15
3	1.38	9.5	0	- 10	- 30	- 30	- 30	- 35
3	0.69	9.5	- 20	- 20	- 30	- 30	- 30	- 55
3	2.76	16.5	+ 20	- 10	- 30	- 30	- 30	- 30
* 1	2.76	9.5	- 10	- 25	- 45	- 30	- 35	- 35
* 2	2.76	9.5	0	- 15	- 20	- 20	- 20	- 20

≠ +15° F. has been added to all 1" plate transition temperature values to compensate for metallurgical differences.

* Split from 3" plate to check against 1" and 2" plate as-rolled for metallurgical differences.

TABLE VIII.1(a) FINAL VAN DER VEEN RESULTS OF TRANSITION TEMPERATURES (^{o}F.)

TEST SPECIMEN			FRACT. APPEAR. CRITERIA		DUCTILITY CRITERIA			
Plate Thickness (in.)	Depth (in.)	Span (in.)	50% Shear	8 mm. Shear	2% Lateral Contraction	0.06" Lateral Contraction	1/2 Defl. at Max. Ductile Load	Drop in Max. Load
3/4	2.76	9.5	- 20	- 45	- 60	-	- 50	- 60
3/4	1.38	9.5	- 25	- 40	- 45	-	- 50	- 60
3/4	0.69	9.5	+ 35	+ 35	- 35	-	- 35	- 40
1-1/2	2.76	9.5	+ 80	+ 20	0	+ 10	+ 10	+ 10
1-1/2	1.38	9.5	+ 80	+ 55	+ 10	+ 30	+ 10	0
1-1/2	0.69	9.5	+ 25	+ 25	- 40	-	- 45	- 50

NOTE: Above are shown the actual uncorrected transition temperatures. Since these plates had Charpy values which indicated they did not have similar heat treatment to the 1", 2", and 3" plates, they are presented alone rather than being compared with those plates.

TABLE VIII.2 RESULTS OF BAGSAR TEST TRANSITION TEMPERATURES (°F.)

TEST SPECIMEN		FRACT. APPEAR. CRITERIA		DUCTILITY CRITERIA		
Plate Thickness (in.)	Depth "D" (in.)	50% Shear	0.75" Shear	2% Lateral Contraction	0.06" Lateral Contraction	Drop in Max. Load
1	1.5	- 5	- 5	- 25	- 25	0
1	3.0	- 5	- 10	- 30	- 25	- 5
1	6.0 (Standard)	- 10	- 10	- 50	- 50	- 40
1	6.0 (Narrow Throat)	- 5	- 15	- 45	- 50	- 40
2	1.5	+ 5	+ 5	- 40	- 40	- 35
2	3.0	+ 20	- 5	- 30	- 45	- 30
2	6.0 (Standard)	+ 30	- 5	- 50	- 55	- 50
2	6.0 (Narrow Throat)	+ 35	+ 25	- 55	- 60	- 55
3	ALL OMITTED					

NOTE: +20° F. has been added to the 1" plate values for all criteria to compensate for metallurgical differences.

TABLE VIII.3 VAN DER VEEN TEST - DATA SHEET

TEST SERIES: 3/4" plate x 2.76" height x 9.5" span

SERIES: 291.AQ

Test No.	% Lateral Contraction at Root of Notch	Load		Deflection at		Test Temp. (^{o}F)	Thumbnail Distance (in.)	Remarks
		Maximum (kips)	Failure (kips)	Max. Load (in.)	Fail. Load (in.)			
1	2.9	37.0	37.0	0.30	0.30	-15	0.02	
2	5.2	46.7	0.8	0.60	2.23	-30	2.55	
3	2.2	34.7	34.7	0.29	0.29	-20	0.02	
4	7.3	48.0	45.0	0.63	0.70	-55	0.42	Cup Fracture
5	7.6	46.0	8.0	0.62	1.47	-40	2.08	
6	0.8	32.5	32.5	0.15	0.15	-75	0	Completely Brittle
7	6.2	42.9	42.9	0.44	0.44	-50	0.11	
8	1.6	35.8	35.8	0.18	0.18	-65	0.01	
9	7.2	47.2	0.4	0.45	2.10	-35	2.50	
10	6.6	47.1	14.0	-	-	-20	1.80	
11	2.1	34.2	34.2	0.26	0.26	-45	0.02	
12	5.9	40.0	40.0	0.50	0.50	0	0.08	
13	9.3	45.7	43.0	0.72	0.79	0	0.50	Cup Fracture
14	9.5	46.0	0.8	0.65	2.40	-15	2.45	
15	0.4	30.3	30.3	0.12	0.12	-60	0	Completely Brittle

TABLE VIII.4 VAN DER VEEN TEST - DATA SHEET

SERIES: 3/4 " plate x 1.38 " height x 9.5 " span SERIES: 291.AR

% Lateral Contraction at Root of Notch	Load		Deflection at		Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
	Maximum (kips)	Failure (kips)	Max. Load (in.)	Fail. Load (in.)			
6.7	9.6	8.0	0.72	0.91	-10	0.40	
7.4	10.1	0.5	0.72	2.70	-30	1.25	
2.9	9.1	9.1	0.35	0.35	-55	0.05	
0.8	7.9	7.9	0.10	0.10	-75	0	Completely Brittle
14.9	9.7	0.4	0.70	2.45	-40	1.18	Cup Fracture
0.8	8.3	8.3	0.17	0.17	-80	0	Completely Brittle
9.3	10.0	0.5	0.70	2.56	0	1.20	Cup Fracture
0.5	7.7	7.7	0.15	0.15	-60	0	Completely Brittle
1.1	8.4	8.4	0.29	0.29	-45	0.02	
7.9	9.8	9.0	0.60	0.74	-50	0.28	
6.0	9.7	9.7	0.59	0.59	-35	0.08	
4.6	10.0	10.0	0.50	0.50	-45	0.06	
8.0	10.0	8.0	0.69	0.94	-25	0.42	
1.3	7.5	7.5	0.12	0.12	-50	0	Completely Brittle
1.2	7.5	7.5	0.24	0.24	-20	0	" "

TABLE VIII.5 VAN DER VEEN TEST - DATA SHEET

SERIES: 3/4 " plate x 0.69 " height x 9.5 " span

SERIES: 291.AS

% Lateral Contraction at Root of Notch	Load		Deflection at		Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
	Maximum (kips)	Failure (kips)	Max. Load (in.)	Fail. Load (in.)			
5.3	2.3	2.1	1.08	1.19	-25	0.10	
0.3	1.3	1.3	0.09	0.09	-80	0	Completely Brittle
5.4	2.4	2.1	1.20	1.37	0	0.12	
2.9	2.4	2.4	1.00	1.00	-60	0.04	
0.8	1.8	1.8	0.44	0.44	-50	0	Completely Brittle
1.1	1.8	1.8	0.21	0.21	-40	0	" "
11.1	2.2	1.6	1.25	1.73	+10	0.25	
9.8	2.2	1.6	1.02	1.44	+15	0.24	
5.4	2.2	2.2	1.07	1.07	+25	0.15	
13.8	2.2	0.9	1.18	2.13	+35	0.35	
7.5	2.1	0.1	1.08	2.87	+45	0.09	
9.1	2.1	1.5	1.13	1.56	+30	0.22	
8.0	2.2	0.1	1.18"	3.00	+40	0.69	Cup Fracture

TABLE VIII.6 VAN DER VEEN TEST - DATA SHEET

SERIES: 1 " plate x 2.76 " height x 9.5 " span SERIES: 291.AA

% Lateral Contraction at Root of Notch	Load		Deflection at		Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
	Maximum (kips)	Failure (kips)	Max. Load (in.)	Fail. Load (in.)			
6.3	69.5	21.0	0.70	1.32	-48	1.75	
10.1	66.8	65.0	0.59	0.63	-70	0.40	
8.3	65.8	60.0	0.60	0.70	-55	0.55	
5.9	62.5	0	0.70	1.73	-20	Full	Ductile Failure
8.0	64.0	41.0	0.59	0.89	-35	1.10	
7.6	67.3	17.5	0.68	1.33	-30	1.92	
8.2	67.0	40.0	0.65	0.96	-40	1.18	
5.7	59.5	52.5	0.72	0.83	-30	0.70	
0.8	49.3	49.3	0.17	0.17	-90	0	
4.4	63.0	0	0.76	2.00	-15	2.50	
6.5	62.3	55.0	0.57	0.69	-100	0.65	
1.8	50.8	50.8	0.18	0.18	-45	1.00	
5.9	62.3	62.3	0.52	0.52	-80	0.17	
7.6	62.0	55.0	0.64	0.78	-25	0.70	
7.2	60.5	0.5	0.70	2.31	-10	2.50	

TABLE VIII.7 VAN DER VEEN TEST - DATA SHEET

TEST SERIES: 1 " plate x 1.38 " height x 9.5 " span

SERIES: 291.AF

Test No.	% Lateral Contraction at Root of Notch	Load: Maximum (kips)	Load: Failure (kips)	Deflection at: Max. Load (in.)	Deflection at: Fail. Load (in.)	Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
1	0.3	13.0	-	0.36	-	-95	0	Brittle Failure
2	1.1	12.3	-	0.23	-	-85	0	" "
3	1.5	12.8	-	0.30	-	-89	0	" "
4	6.6	13.9	-	0.65	-	-40	-	Partly Ductile
5	7.8	13.7	-	0.74	-	-20	-	Partly Ductile
6	8.4	14.4	-	0.72	-	-55	-	Partly Ductile
7	0.4	11.7	-	0.09	-	-75	0	Brittle Failure
8	0.6	12.7	-	0.12	-	-103	0	" "
9	0.4	12.6	-	0.06	-	-114	0	" "
10	8.0	14.0	-	0.66	-	-49	-	Partly Ductile
11	1.5	12.2	-	0.18	-	-81	0	Brittle Failure
12	1.0	12.3	-	0.24	-	-60	0	" "
13	0.5	11.6	-	0.09	-	-68	0	" "
14	1.0	12.1	-	0.16	-	-90	0	" "
15	0.3	12.2	-	0.06	-	-97	0	" "

TABLE VIII.7 VAN DER VEEN TEST - DATA SHEET

SERIES: 1 " plate x 1.38 " height x 9.5 " span (cont'd.)

SERIES: 291.AF

% Lateral Contraction at Root of Notch	Load		Deflection at		Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
	Maximum (kips)	Failure (kips)	Max. Load (in.)	Fail. Load (in.)			
8.9	14.1	0.7	0.75	2.48	-48	-	99% Ductile
0.4	12.1	12.1	0.11	0.11	-52	0	Brittle Failure
0	11.5	11.5	0.16	0.16	-60	0	" "
0	11.4	11.4	0.18	0.18	-44	0.07	
2.0	11.9	1.5	0.30	0.88	-40	-	99% Ductile
5.4	11.4	1.2	0.35	1.03	-30	1.30	
5.1	11.1	0.2	0.37	1.36	-20	1.30	
4.5	11.0	0.1	0.33	1.53	-35	1.25	

TABLE VIII.8 VAN DER VEEN TEST - DATA SHEET

TEST SERIES: 1" plate x 0.69" height x 9.5" span

SERIES: 291.AJ

Test No.	% Lateral Contraction at Root of Notch	Load Maximum (kips)	Load Failure (kips)	Deflection at Max. Load (in.)	Deflection at Fail. Load (in.)	Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
1	9.1	3.0	-	1.04	-	+82	-	Completely Ductile
2	4.5	2.9	-	0.98	-	+82	-	" "
3	3.2	3.0	-	0.81	-	-34	-	
4	3.5	2.9	-	0.93	-	+1	-	
5	3.7	3.2	-	0.97	-	+18	-	
6	0.3	2.7	-	0.17	-	-92	-	Completely Brittle
7	0.1	2.9	-	0.14	-	-112	-	" "
8	0	2.6	-	0.10	-	-94	-	" "
9	0.2	2.8	-	0.15	-	-99	-	" "
10	0	2.9	-	0.14	-	-120	-	" "
11	0.6	3.1	-	0.28	-	-100	-	Completely Brittle
12	3.4	3.1	-	0.69	-	-90	-	
13	3.4	3.1	-	0.73	-	-62	-	
14	4.2	3.5	-	0.98	-	-100	-	
15	3.9	3.4	-	0.89	-	-100	-	

TABLE VIII.8 VAN DER VEEN TEST - DATA SHEET

SERIES: 1" plate x 0.69" height x 9.5" span (cont'd.)

SERIES: 291.AJ

% Lateral Contraction at Root of Notch	Load		Deflection at		Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
	Maximum (kips)	Failure (kips)	Max. Load (in.)	Fail. Load (in.)			
0.4	2.8	2.8	0.24	0.24	-70	0	
5.7	3.3	1.1	0.88	1.71	-80	0.40	
0.1	2.8	2.8	0.20	0.20	-90	0	
0	2.8	2.8	0.21	0.21	-100	0	
6.8	3.2	0	0.70	2.28	-50	full	Completely Ductile
6.4	3.0	0.8	0.67	1.82	-60	0.40	
7.7	3.0	0	1.00	3.16	-30	full	Completely Ductile
5.9	3.0	0	0.82	2.60	-40	full	Completely Ductile

TABLE VIII.9 VAN DER VEEN TEST - DATA SHEET

SERIES: 1 " plate x 2.76 " height x 16.5 " span SERIES: 291.AM

% Lateral Contraction at Root of Notch	Load: Maximum (kips)	Load: Failure (kips)	Deflection at: Max. Load (in.)	Deflection at: Fail. Load (in.)	Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
10.2	34.4	-	1.20	-	-57	-	
10.4	34.0	-	1.15	-	-60	-	
10.9	35.6	-	1.32	-	-68	-	
11.3	32.9	-	1.19	-	-5	-	
3.4	31.7	-	0.68	-	-72	0.05	
9.7	33.3	2.8	1.28	1.52	-50	0.63	
5.5	33.3	33.3	0.95	0.95	-80	0.10	
0.8	27.5	27.5	0.21	0.21	-100	0	Brittle Failure
3.3	31.5	-	0.60	-	-89	0.02	
11.0	32.8	-	1.08	-	-27	-	
9.2	31.5	31.5	0.95	-	-40	2.08	
5.4	33.4	-	1.16	-	-30	1.50	
5.6	33.5	-	1.11	-	-60	2.10	
8.3	33.3	-	1.08	-	-65	0.25	
10.3	35.0	-	1.23	-	-70	0.70	

TABLE VIII.10 VAN DER VEEN TEST - DATA SHEET

TEST SERIES: 1 " plate x 2.76 " height x 9.5 " span (split from 3" plate) SERIES: 291.AD

Test No.	% Lateral Contraction at Root of Notch	Load Maximum (kips)	Load Failure (kips)	Deflection at Max. Load (in.)	Deflection at Fail. Load (in.)	Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
1	11.0	63.0	60.0	0.82	0.89	-30	0.42	
2	1.9	44.3	44.3	0.22	0.22	-40	0	Completely Brittle
3	10.9	64.5	62.0	0.83	0.87	-10	0.33	
4	3.3	52.8	52.8	0.31	0.31	-50	0.02	
5	1.0	44.3	44.3	0.15	0.15	-60	0	Completely Brittle
6	13.7	63.8	7.5	0.75	1.93	+10	2.20	
7	8.5	66.0	15.0	0.76	1.50	-15	1.94	
8	10.9	61.3	1.0	0.69	2.65	+20	Full	Completely Ductile
9	7.1	64.5	52.5	0.76	0.96	-20	0.73	
10	8.5	63.0	52.5	0.75	0.82	-10	0.45	
11	8.3	64.3	12.5	0.76	1.51	0	2.00	

TABLE VIII.11 VAN DER VEEN TEST - DATA SHEET

TEST SERIES: 1½" plate x 2.76" height x 9.5" span

SERIES: 291.AV

Test No.	% Lateral Contraction at Root of Notch	Load Maximum (kips)	Load Failure (kips)	Deflection at Max. Load (in.)	Deflection at Fail. Load (in.)	Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
1	8.3	91.0	88.0	0.79	0.88	+65	0.50	
2	8.6	94.0	91.0	0.82	0.89	+50	0.38	
3	2.5	77.0	77.0	0.34	0.34	+10	0.02	
4	2.0	71.0	71.0	0.27	0.27	0	0	Completely Brittle
5	5.8	90.0	90.0	0.60	0.60	+15	0.10	
6	7.3	91.5	2.0	0.78	2.39	+95	2.50	
7	8.2	88.0	37.0	0.80	1.26	+85	1.70	
8	1.1	63.8	63.8	0.19	0.19	-25	0	Completely Brittle
9	7.0	90.0	2.0	0.76	2.35	+100	2.50	
10	10.1	96.5	93.0	0.84	0.88	+25	0.45	
11	1.4	63.0	63.0	0.20	0.20	-10	0	Completely Brittle
12	8.3	91.5	60.0	0.75	1.08	+90	1.20	
13	13.6	92.5	2.0	0.70	2.22	+40	2.50	Cup Fracture
14	7.4	96.0	2.0	0.84	3.20	+75	2.50	Cup Fracture
15	5.9	92.0	2.0	0.84	2.25	+80	2.50	

TABLE VIII.12 VAN DER VEEN TEST - DATA SHEET

SERIES: 1½" plate x 1.38" height x 9.5" span

SERIES: 291.AT

% Lateral Contraction at Root of Notch	Load Maximum (kips)	Load Failure (kips)	Deflection at Max. Load (in.)	Deflection at Fail. Load (in.)	Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
4.8	20.4	20.4	0.81	0.81	+52	0.12	
8.8	20.8	6.5	0.96	1.86	+80	1.05	
5.7	20.4	20.4	0.97	0.97	+90	0.13	
13.6	19.8	1.5	0.95	2.41	+100	1.10	Cup Fracture
8.1	20.4	17.5	0.95	1.20	+60	0.40	
7.3	20.8	5.5	0.98	1.82	+85	0.90	Cup Fracture
2.3	19.2	19.2	0.60	0.60	+10	0.04	
2.6	19.7	19.7	0.61	0.61	+15	0.05	
4.0	21.0	21.0	0.80	0.80	+35	0.10	
0.5	12.8	12.8	0.11	0.11	0	0	Completely Brittle
1.5	17.7	17.7	0.34	0.34	+5	0.02	
7.5	21.6	18.0	1.05	1.25	+70	0.45	
7.2	21.1	20.0	1.05	1.09	+75	0.20	
5.1	20.8	20.8	0.97	0.97	+45	0.12	
6.9	22.2	21.5	0.95	1.06	+25	0.24	

TABLE VIII.13 VAN DER VEEN TEST - DATA SHEET

SERIES: 1½" plate x 0.69" height x 9.5" span

SERIES: 291.AU

% Lateral Contraction at Root of Notch	Load		Deflection at		Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
	Maximum (kips)	Failure (kips)	Max. Load (in.)	Fail. Load (in.)			
5.0	4.9	3.5	1.20	1.61	-5	0.18	
3.8	4.7	0.1	1.24	3.50	+25	0.69	Cup Fracture
4.2	5.0	1.7	1.22	2.29	-22	0.36	
4.0	4.9	4.0	1.15	1.36	-10	0.15	
2.7	4.5	4.5	1.09	1.09	-25	0.07	
0.5	4.0	4.0	0.45	0.45	-50	0	Completely Brittle
0.6	4.2	4.2	0.35	0.35	-70	0	" "
2.3	4.9	4.9	0.95	0.95	-40	0.05	
3.4	5.2	5.1	1.13	1.29	-30	0.08	
3.4	4.7	4.4	1.29	1.50	+20	0.10	
4.2	4.8	4.0	1.24	1.52	+10	0.15	
3.8	5.1	3.8	1.22	1.55	+30	0.20	
4.3	4.7	0.1	1.10	3.0 +	+15	0.69	Cup Fracture
3.8	5.0	0.1	1.18	3.0 +	+35	0.69	
4.1	4.8	2.4	1.12	1.81	+20	0.30	

TABLE VIII.14 VAN DER VEEN TEST - DATA SHEET

SERIES: 2" plate x 2.76" height x 9.5" span

SERIES: 291.AB

% Lateral Contraction at Root of Notch	Load: Maximum (kips)	Load: Failure (kips)	Deflection at Max. Load (in.)	Deflection at Fail. Load (in.)	Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
8.3	136.8	22.5	0.85	1.56	+20	2.3	
7.3	137.5	137.5	0.77	0.77	-15	0.4	
0.9	96.0	96.0	0.15	0.15	-78	0	
2.1	109.3	109.3	0.33	0.33	-51	0.02	
2.9	117.0	117.0	0.39	0.39	-42	0.03	
8.2	142.8	140.0	0.83	0.88	-30	0.52	
8.4	140.3	135.0	0.83	0.91	-20	0.60	
2.4	108.5	108.5	0.36	0.36	-35	0.02	
9.4	139.3	25.0	0.82	1.55	-10	2.10	
8.4	140.0	25.0	0.76	1.57	+15	2.40	
6.3	133.8	133.8	0.75	0.75	0	0.30	
7.6	140.0	140.0	0.89	0.89	-5	0.35	
7.0	143.5	143.5	0.96	1.06	-10	0.55	
-	-	-	-	-	-	-	discarded-poor notch
6.8	140.8	47.5	0.93	1.55	+10	1.90	

TABLE VIII.15 VAN DER VEEN TEST - DATA SHEET

SERIES: 2" plate x 1.38" height x 9.5" span

SERIES: 291.AG

% Lateral Contraction at Root of Notch	Load		Deflection at		Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
	Maximum (kips)	Failure (kips)	Max. Load (in.)	Fail. Load (in.)			
0.3	24.3	-	0.20	-	-69	0	Brittle Failure
4.9	33.4	-	0.90	-	-36	-	
0.5	23.1	-	0.20	-	0	-	
5.5	31.5	-	0.79	-	-10	-	
1.5	27.6	-	0.43	-	-24	0.02	
5.2	24.0	-	0.95	1.28	-20	0.48	
0.6	22.4	22.4	0.20	0.20	-50	0	Brittle Failure
1.2	22.4	22.4	0.21	0.21	-40	0	" "
6.9	31.7	2.5	0.93	2.35	0	1.10	
6.3	31.5	30.0	0.96	1.06	-10	0.30	
4.9	33.0	-	1.04	-	-27	0.70	
3.6	33.4	-	1.06	-	-20	0.80	
6.7	30.6	-	0.86	-	-4	1.15	
3.9	30.4	-	0.85	-	-31	0.12	
6.2	32.2	-	0.95	-	-35	0.22	

TABLE VIII.16 VAN DER VEEN TEST - DATA SHEET

TEST SERIES: 2 " plate x 0.69 " height x 9.5 " span

SERIES: 291.AK

Test No.	% Lateral Contraction at Root of Notch	Load Maximum (kips)	Load Failure (kips)	Deflection at Max. Load (in.)	Deflection at Fail. Load (in.)	Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
1	2.3	6.6	-	1.13	-	+10	-	
2	0	5.4	-	0.32	-	-20	0	Brittle Failure
3	3.4	6.9	-	1.19	-	-5	-	
4	0	5.8	-	0.33	-	-65	0	Brittle Failure
5	0	4.8	-	0.14	-	-34	0	" "
6	4.9	7.1	-	1.34	-	-18	-	
7	4.1	7.1	-	1.35	-	-30	-	
8	4.7	7.1	-	1.15	-	-27	0.50	
9	4.1	7.0	-	1.27	-	-24	0.50	
10	2.8	7.0	-	1.05	-	-32	0.10	
11	0.2	5.5	-	0.28	-	-30	0	Brittle Failure
12	4.5	7.1	-	1.10	-	-28	-	
13	3.2	6.9	6.5	1.15	1.33	-30	0.12	
14	0.1	4.8	4.8	0.14	0.14	-40	0	Brittle Failure
15	0.2	4.7	4.7	0.13	0.13	-50	0	" "

TABLE VIII.17 VAN DER VEEN TEST - DATA SHEET

TEST SERIES: 2" plate x 2.76" height x 16.5" span

SERIES: 291.AN

Test No.	% Lateral Contraction at Root of Notch	Load Maximum (kips)	Load Failure (kips)	Deflection at Max. Load (in.)	Deflection at Fail. Load (in.)	Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
1	7.6	71.0	67.5	1.49	1.65	+10	0.50	
2	8.9	69.0	10.0	1.55	3.06	+20	2.30	
3	1.5	54.8	54.8	0.37	0.37	-60	0.02	
4	1.9	59.0	59.0	0.53	0.53	-70	0.03	
5	1.8	61.5	61.5	0.61	0.61	-50	0.04	
6	8.2	74.5	72.5	1.65	1.77	-40	0.40	
7	6.9	73.0	72.5	1.53	1.64	-30	0.38	
8	6.6	70.8	2.5	1.66	4.35	+30	2.35	
9	7.8	74.3	70.0	1.58	1.74	-20	0.46	
10	7.6	73.0	17.5	1.67	2.97	+5	1.90	
11	6.4	75.3	75.3	1.84	1.84	-45	0.26	
12	7.7	70.5	70.5	1.64	1.64	+10	0.30	
13	10.2	73.0	62.5	1.81	2.19	+15	0.80	
14	9.2	77.5	65.0	1.79	2.15	-10	0.65	
15	9.6	71.5	40.0	1.79	2.38	0	1.02	

TABLE VIII.18 VAN DER VEEN TEST - DATA SHEET

TEST SERIES: 2 " plate x 2.76 " height x 9.5 " span (split from 3" plate)

SERIES: 291.AE

Test No.	% Lateral Contraction at Root of Notch	Load: Maximum (kips)	Load: Failure (kips)	Deflection at: Max. Load (in.)	Deflection at: Fail. Load (in.)	Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
1	8.1	138.0	47.5	0.86	1.43	+20	2.00	
2	7.6	141.5	27.5	0.90	1.58	+10	2.30	
3	7.6	135.0	130.0	0.82	0.88	0	0.66	
4	0.3	90.8	90.8	0.15	0.15	-80	0	Completely Brittle
5	6.9	138.3	138.3	0.87	0.87	-15	0.44	
6	7.9	137.3	125.0	0.89	0.99	-5	0.72	
7	9.5	139.3	35.0	0.88	1.59	+5	1.90	
8	0.4	95.5	95.5	0.26	0.26	-40	0	Completely Brittle
9	1.7	98.5	98.5	0.28	0.28	-30	0.02	
10	1.7	111.0	111.0	0.38	0.38	-20	0.02	
11	7.8	145.0	140.0	0.93	0.96	-10	0.44	

TABLE VIII.19 VAN DER VEEN TEST - DATA SHEET

TEST SERIES: 3 " plate x 2.76 " height x 9.5 " span

SERIES: 291.AC

Test No.	% Lateral Contraction at Root of Notch	Load		Deflection at		Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
		Maximum (kips)	Failure (kips)	Max. Load (in.)	Fail. Load (in.)			
1	8.9	214.0	207.5	1.05	1.17	+10	0.60	
2	1.0	150.0	150.0	0.26	0.26	-30	0.01	
3	6.8	214.0	192.5	0.92	1.11	+5	0.70	
4	4.2	195.0	195.0	0.58	0.58	-10	0.10	
5	5.1	208.5	208.5	0.88	0.88	-5	0.30	
6	5.8	202.0	200.0	0.76	0.79	0	0.54	
7	2.9	183.0	183.0	0.45	0.45	-15	0.04	
8	8.0	206.5	100.0	0.83	1.29	+15	1.50	
9	8.3	211.0	60.0	0.90	1.57	+30	2.10	
10	1.6	160.0	160.0	0.29	0.29	-40	0.02	
11	-	-	-	-	-	-	-	discarded-poor notch
12	6.7	210.0	2.5	0.86	2.27	+20	2.50	
13	0.4	127.0	127.0	0.15	0.15	-20	0	Completely Brittle
14	5.1	203.0	203.0	0.74	0.74	+5	0.25	
15	7.2	208.5	17.5	0.87	1.75	+15	2.40	

TABLE VIII.20 VAN DER VEEN TEST - DATA SHEET

TEST SERIES: 3 " plate x 1.38 " height x 9.5 " span SERIES: 291.AH

Test No.	% Lateral Contraction at Root of Notch	Load		Deflection at		Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
		Maximum (kips)	Failure (kips)	Max. Load (in.)	Fail. Load (in.)			
1	4.3	48.3	-	0.89	-	-1	-	
2	0.6	34.3	-	0.19	-	-40	0	Completely Brittle
3	4.1	46.0	-	0.83	-	-20	-	
4	0.3	33.0	-	0.12	-	-50	0	Completely Brittle
5	4.2	48.0	10.0	1.03	1.79	+20	1.00	
6	3.9	47.3	47.3	0.95	0.95	+10	0.20	
7	4.1	48.6	48.0	1.09	1.17	-10	0.30	
8	3.1	43.7	-	0.79	-	-5	1.00	
9	4.2	47.2	-	0.96	-	+2	0.30	
10	2.7	49.3	-	0.78	-	-25	0.08	
11	4.7	47.8	-	1.10	-	-9	0.45	
12	3.1	47.6	-	0.86	-	-19	0.25	
13	2.0	47.0	-	0.66	-	-15	0.08	
14	3.2	48.2	-	0.95	-	-21	0.15	
15	3.8	49.4	-	1.00	-	-17	0.70	

TABLE VIII.21 VAN DER VEEN TEST - DATA SHEET

TEST SERIES: 3 " plate x 0.69" height x 9.5" span

SERIES: 291.AL

Test No.	% Lateral Contraction at Root of Notch	Load: Maximum (kips)	Load: Failure (kips)	Deflection at: Max. Load (in.)	Deflection at: Fail. Load (in.)	Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
1	2.9	10.3	7.8	1.25	1.69	-20	0.20	
2	3.1	9.5	1.0	1.20	3.26	+20	-	
3	3.1	9.3	1.9	1.20	2.96	+10	0.44	
4	0.2	7.4	7.4	0.19	0.19	-60	0	Completely Brittle
5	1.4	9.3	9.3	1.12	1.12	-50	0.06	
6	2.1	9.7	1.0	1.17	3.50	-30	0.47	
7	3.9	10.5	2.4	1.27	2.73	-10	0.45	
8	1.5	10.0	10.0	1.10	1.10	-40	0.10	
9	0.1	7.2	7.2	0.19	0.19	-70	0	Completely Brittle
10	3.2	10.0	0.8	1.19	4.26	0	Full	Completely Ductile
11	0.4	7.8	7.8	0.36	0.36	-25	0.01	
12	0.2	6.7	6.7	0.17	0.17	-80	0	Completely Brittle
13	2.9	10.1	2.3	1.09	2.45	-15	0.44	
14	0.1	6.9	6.9	0.18	0.18	-30	0	Completely Brittle
15	0.7	8.9	8.9	0.58	0.58	-35	0.01	

TABLE VIII.22 VAN DER VEEN TEST - DATA SHEET

TEST SERIES: 3 " plate x 2.96 " height x 16.5 " span

SERIES: 291.AP

Test No.	% Lateral Contraction at Root of Notch	Load Maximum (kips)	Load Failure (kips)	Deflection at Max. Load (in.)	Deflection at Fail. Load (in.)	Test Temp. (°F)	Thumbnail Distance (in.)	Remarks
1	11.4	112.0	85.0	2.47	3.35	+10	0.90	
2	0.6	71.0	71.0	0.23	0.23	-30	0	Completely Brittle
3	8.6	110.0	10.0	2.05	4.01	+35	2.10	
4	9.4	113.0	105.0	1.90	2.23	0	0.60	
5	6.2	111.0	111.0	1.75	1.75	-20	0.20	
6	8.5	109.0	80.0	1.70	2.15	-10	1.10	
7	2.1	92.0	92.0	0.63	0.63	-40	0.03	
8	7.7	110.0	20.0	1.85	3.17	+30	2.30	
9	6.5	115.5	115.5	1.77	1.77	-25	0.25	
10	8.2	109.0	102.5	1.80	1.49	+20	0.60	
11	-	-	-	-	-	-	-	discarded-short height
12	7.2	108.0	32.5	1.75	2.75	+15	1.80	
13	8.1	110.0	100.0	1.70	2.01	+25	0.60	
14	7.2	108.0	67.5	1.68	2.29	+20	1.20	
15	8.7	109.0	20.0	1.45	3.58	+30	2.30	

TABLE VIII.23 BAGSAR TEST - DATA SHEET

TEST SERIES: 1 " plate x 6 " depth

SERIES: 291.AA

Test No.	% Lateral Contraction at Root of Notch	Load: Maximum (kips)	Load: Failure (kips)	Test Temperature (^oF)	Thumbnail Distance (in.)	Remarks
1	8.6	120.0	10.0	0	4.77	
2	8.3	121.0	8.0	-25	5.00	
3	4.4	118.0	118.0	-50	0.40	
4	8.2	122.0	100.0	-30	0.85	
5	7.1	120.5	120.5	-40	0.17	
6	6.2	117.1	117.1	-58	0.14	
7	1.9	108.0	108.0	-90	0.02	
8	0.8	100.5	100.5	-70	0	Completely Brittle
9	6.7	121.0	121.0	-65	0.30	
10	1.3	104.0	104.0	-76	0	Completely Brittle.

TABLE VIII.24 BAGSAR TEST - DATA SHEET

TEST SERIES: 1 " plate x 3 " depth SERIES: 291.AB

Test No.	% Lateral Contraction at Root of Notch	Load Maximum (kips)	Load Failure (kips)	Test Temperature (°F)	Thumbnail Distance (in.)	Remarks
1	11.9	50.0	-	0	Full	Completely Ductile
2	5.6	50.0	14.0	-25	1.95	
3	1.0	43.0	43.0	-50	0	Completely Brittle
4	8.5	52.0	22.0	-20	1.70	
5	6.0	52.5	48.0	-35	0.53	
6	2.0	44.0	44.0	-60	0.02	
7	6.5	51.7	8.0	-15	2.30	
8	0.7	40.0	40.0	-85	0	Completely Brittle
9	1.5	39.0	39.0	-55	0	" "
10	4.0	50.0	46.5	-30	0.70	

TABLE VIII.25 BAGSAR TEST - DATA SHEET

TEST SERIES: 1" plate x 1½" depth

SERIES: 291.AC

Test No.	% Lateral Contraction at Root of Notch	Load Maximum (kips)	Load Failure (kips)	Test Temperature (°F)	Thumbnail Distance (in.)	Remarks
1	6.5	24.2	8.2	-10	1.35	
2	4.6	26.0	22.0	-25	0.50	
3	5.1	23.0	9.0	-20	1.00	
4	7.4	26.5	26.5	-35	0.35	
5	7.7	25.0	16.0	-15	0.75	
6	5.0	24.5	8.5	-20	1.25	
7	0.5	13.0	13.0	-50	0	Completely Brittle
8	6.5	26.0	10.0	0	1.50	
9	4.1	20.0	20.0	-45	0.12	
10	0.4	14.8	14.8	-55	0	Completely Brittle

TABLE VIII.26 BAGSAR TEST - DATA SHEET

TEST SERIES: 1 " plate x 6 " depth (narrow throat)

SERIES: 291.AD

Test No.	% Lateral Contraction at Root of Notch	Load Maximum (kips)	Load Failure (kips)	Test Temperature (°F)	Thumbnail Distance (in.)	Remarks
1	7.1	113.0	30.0	0	3.30	
2	5.8	110.0	110.0	-25	0.10	
3	9.0	124.0	124.0	-50	0.30	
4	8.5	113.0	2.0	-10	5.80	
5	9.0	117.0	9.0	-20	4.90	
6	1.7	105.0	105.0	-75	0.02	
7	1.9	108.0	108.0	-65	0.02	
8	0.7	100.0	100.0	-85	0	Completely Brittle
9	7.5	120.0	50.0	-30	2.33	
10	7.4	115.0	12.0	-25	4.50	

TABLE VIII.27 BAGSAR TEST - DATA SHEET

TEST SERIES: 2 " plate x 6 " depth

SERIES: 291.AE

Test No.	% Lateral Contraction at Root of Notch	Load Maximum (kips)	Load Failure (kips)	Test Temperature (^{o}F)	Thumbnail Distance (in.)	Remarks
1	8.9	257.0	257.0	+25	0.55	
2	6.8	266.6	266.6	-25	0.32	
3	8.3	273.8	273.8	-43	0.28	
4	3.1	226.0	226.0	-50	0.05	
5	0.7	190.0	190.0	-55	0	Completely Brittle
6	1.3	210.0	210.0	-65	0	" "
7	7.2	247.0	4.0	+50	5.70	
8	5.0	266.0	140.0	+2	2.20	
9	8.8	268.0	200.0	+15	1.50	
10	8.5	257.0	8.0	+36	5.40	

TABLE VIII.28 BAGSAR TEST - DATA SHEET

TEST SERIES: 2 " plate x 3 " depth

SERIES: 291.AF

Test No.	% Lateral Contraction at Root of Notch	Load Maximum (kips)	Load Failure (kips)	Test Temperature (°F)	Thumbnail Distance (in.)	Remarks
1	6.5	128.6	128.6	-25	0.34	
2	6.3	123.0	100.0	0	1.00	
3	6.2	116.0	8.0	+25	2.70	
4	8.2	116.0	62.0	+20	1.50	
5	4.0	111.0	111.0	-10	0.08	Cup Fracture
6	8.4	122.0	80.0	+15	1.15	" "
7	2.1	92.0	92.0	-30	0.02	
8	2.5	98.0	98.0	-35	0.03	
9	1.8	87.7	87.7	-60	0	Completely Brittle
10	2.7	95.0	95.0	-50	0.03	

TABLE VIII.29 BAGSAR TEST - DATA SHEET

TEST SERIES: 2 " plate x 1½ " depth SERIES: 291.AG

Test No.	% Lateral Contraction at Root of Notch	Load		Test Temperature (°F)	Thumbnail Distance (in.)	Remarks
		Maximum (kips)	Failure (kips)			
1	7.5	60.0	20.0	+20	1.20	Cup Fracture
2	5.7	59.0	10.0	+25	1.50	
3	8.6	64.5	50.0	0	0.60	Cup Fracture
4	6.3	67.0	60.0	+15	0.57	
5	8.6	61.0	15.0	+10	1.20	Cup Fracture
6	3.7	56.0	56.0	-10	0.27	
7	0.5	30.0	30.0	-50	0	Completely Brittle
8	1.8	37.0	37.0	-40	0.02	
9	6.4	63.0	17.0	+5	1.15	Cup Fracture
10	5.9	66.5	66.5	-35	0.18	

TABLE VIII.30 BAGSAR TEST - DATA SHEET

TEST SERIES: 2 " plate x 6 " depth (narrow throat) SERIES: 291.AH

Test No.	% Lateral Contraction at Root of Notch	Load: Maximum (kips)	Load: Failure (kips)	Test Temperature (°F)	Thumbnail Distance (in.)	Remarks
1	10.4	264.0	264.0	+12	0.38	
2	13.3	264.0	263.0	0	0.30	
3	11.2	258.0	258.0	+20	0.60	Cup Fracture
4	9.3	259.0	240.0	+25	0.80	
5	8.0	264.0	264.0	-25	0.23	
6	4.6	240.0	240.0	-50	0.06	
7	-	257.5	5.0	+30	full	Completely Ductile
8	1.0	200.0	200.0	-60	0	Completely Brittle
9	11.5	264.0	188.0	+35	1.70	
10	10.5	256.0	12.0	+45	5.25	

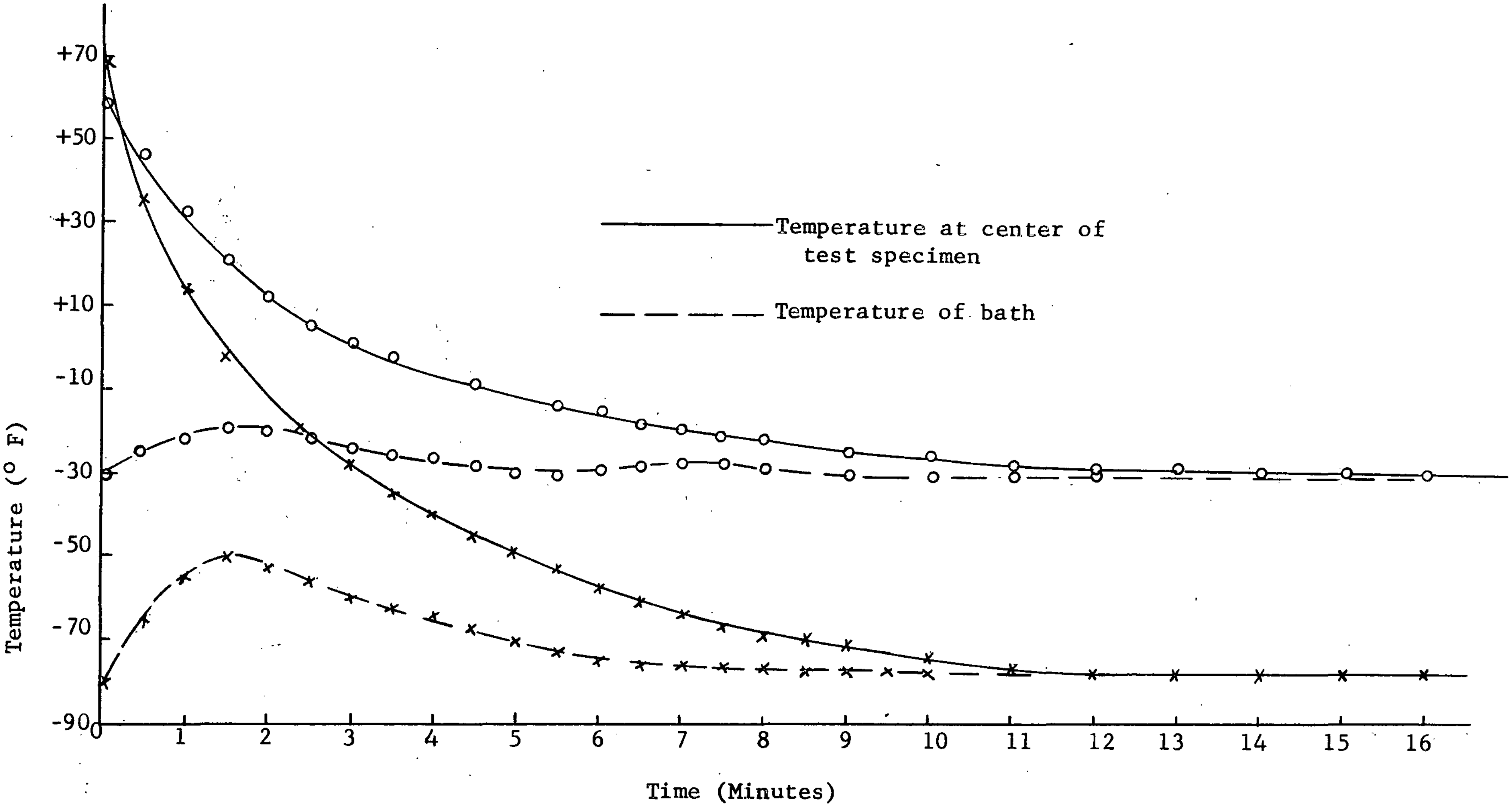


Fig. 8.1 TIME OF COOLING CURVE FOR 3" x 2.76" X-SECTION VAN DER VEEN SPECIMEN IN ALCOHOL AND DRY ICE BATH COOLED FROM ROOM TEMPERATURE TO -30° F. and -75° F.

Van der Veen Tests

RELATIVE STRESS RATIOS AT 50% SHEAR

Specimen Depth (inch)	Breaking Load (kips)	Relative Stress Ratio
Full	35.0	1.00
1/2 Full	7.0	0.80
1/4 Full	1.5	0.69

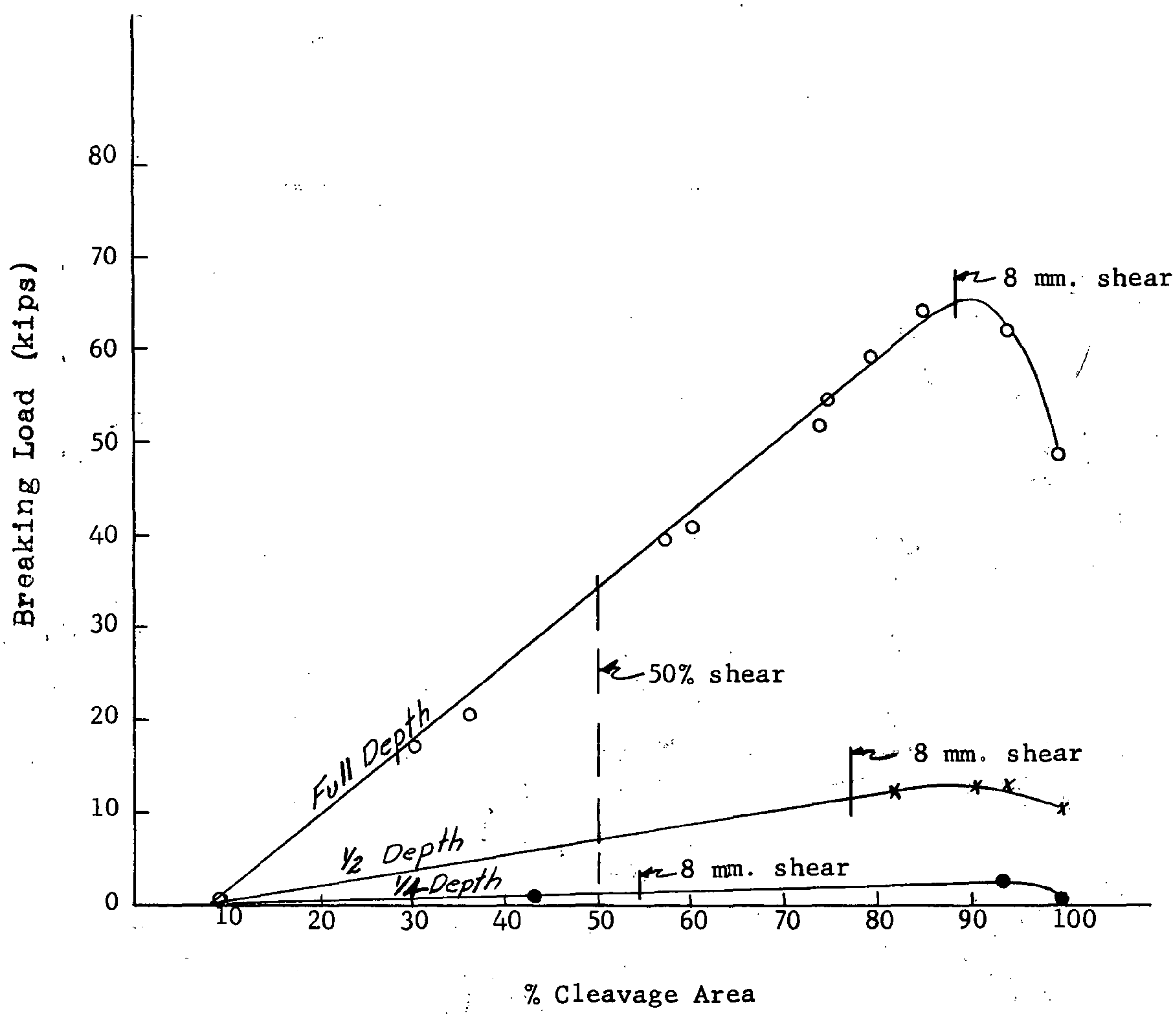


Fig. 8.2 BREAKING LOAD vs. PERCENT CLEAVAGE AREA FOR 1-INCH PLATE THICKNESS OF VARYING DEPTHS

Van der Veen Tests

RELATIVE STRESS RATIOS AT 50% SHEAR

Specimen Depth (inch)	Breaking Load (kips)	Relative Stress Ratio
Full	87.0	1.00
1/2 Full	17.0	0.78
1/4 Full	3.7	0.69

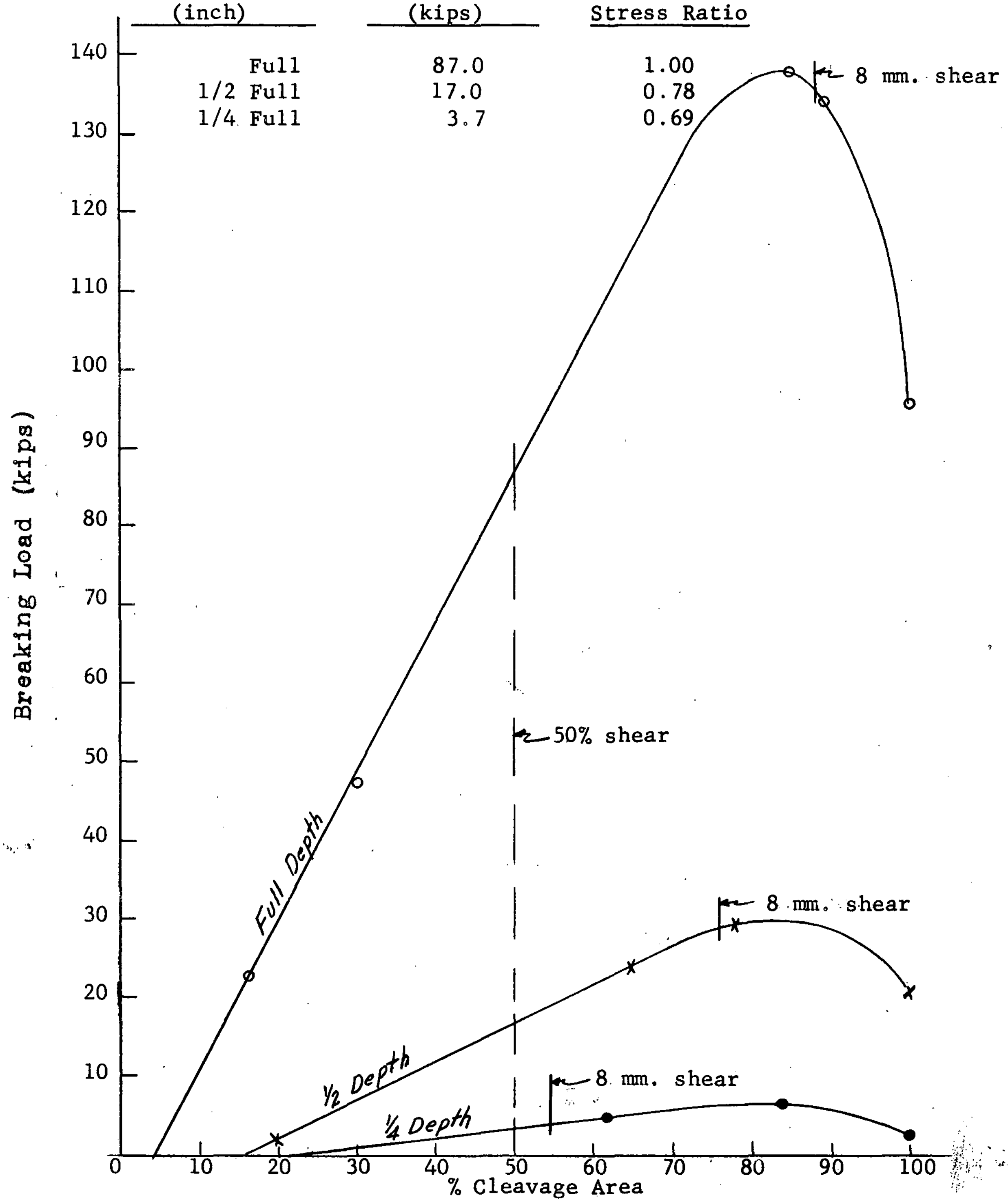


Fig. 8.3 BREAKING LOAD vs. PERCENT CLEAVAGE AREA FOR 2-INCH PLATE THICKNESS OF VARYING DEPTHS

Van der Veen Tests

RELATIVE STRESS RATIOS AT 50% SHEAR

Specimen Depth (inch)	Breaking Load (kips)	Relative Stress Ratio
Full	140.0	1.00
1/2 Full	28.0	0.80
1/4 Full	6.0	0.69

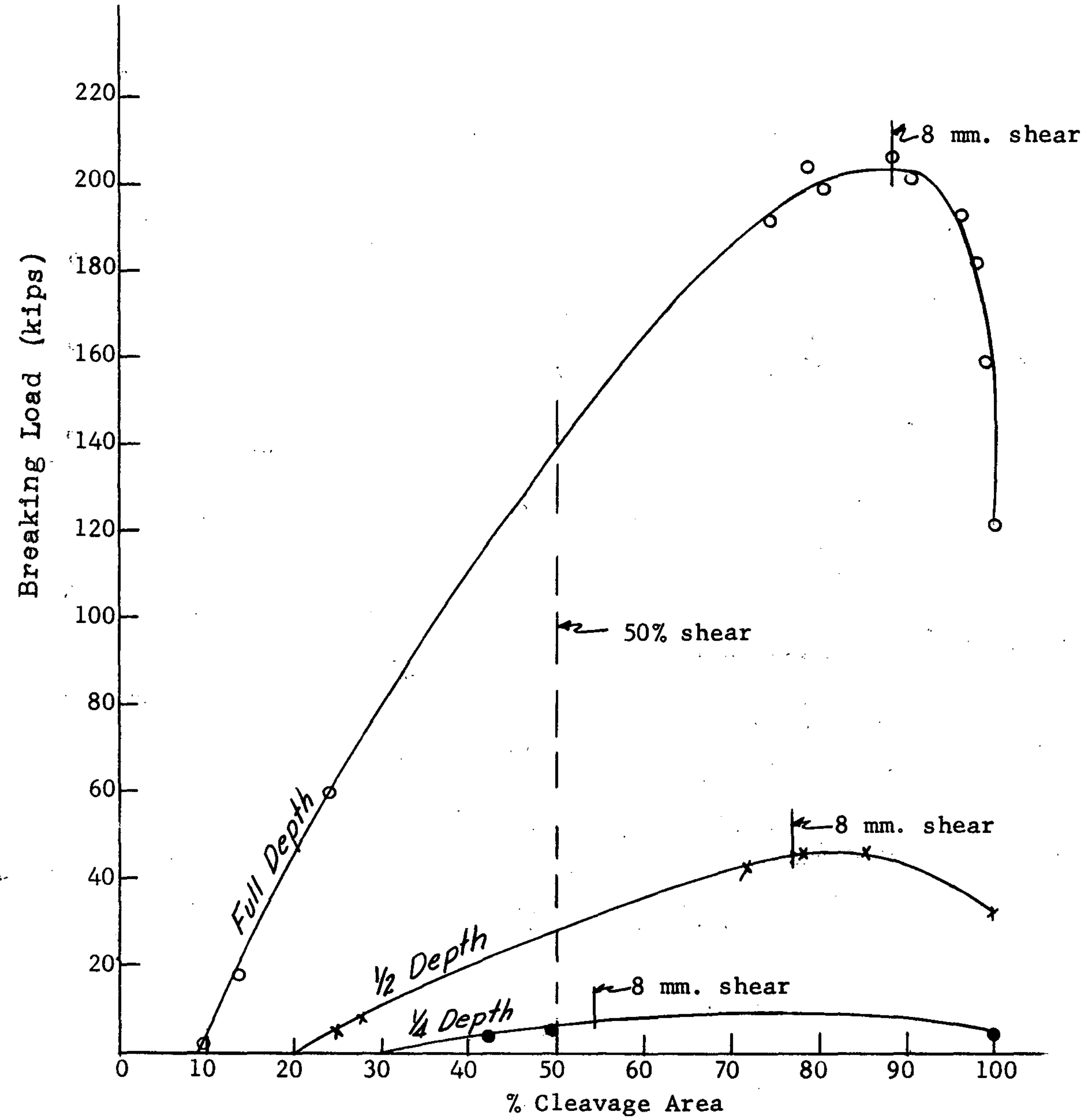


Fig. 8.4 BREAKING LOAD vs. PERCENT CLEAVAGE AREA FOR 3-INCH PLATE THICKNESS OF VARYING DEPTHS

Van der Veen Tests

RELATIVE STRESS RATIOS AT 50% SHEAR

Specimen Thickness (inch)	Breaking Load (kips)	Relative Stress Ratio
1	140.0	0.75
2	87.0	0.93
3	35.0	1.00

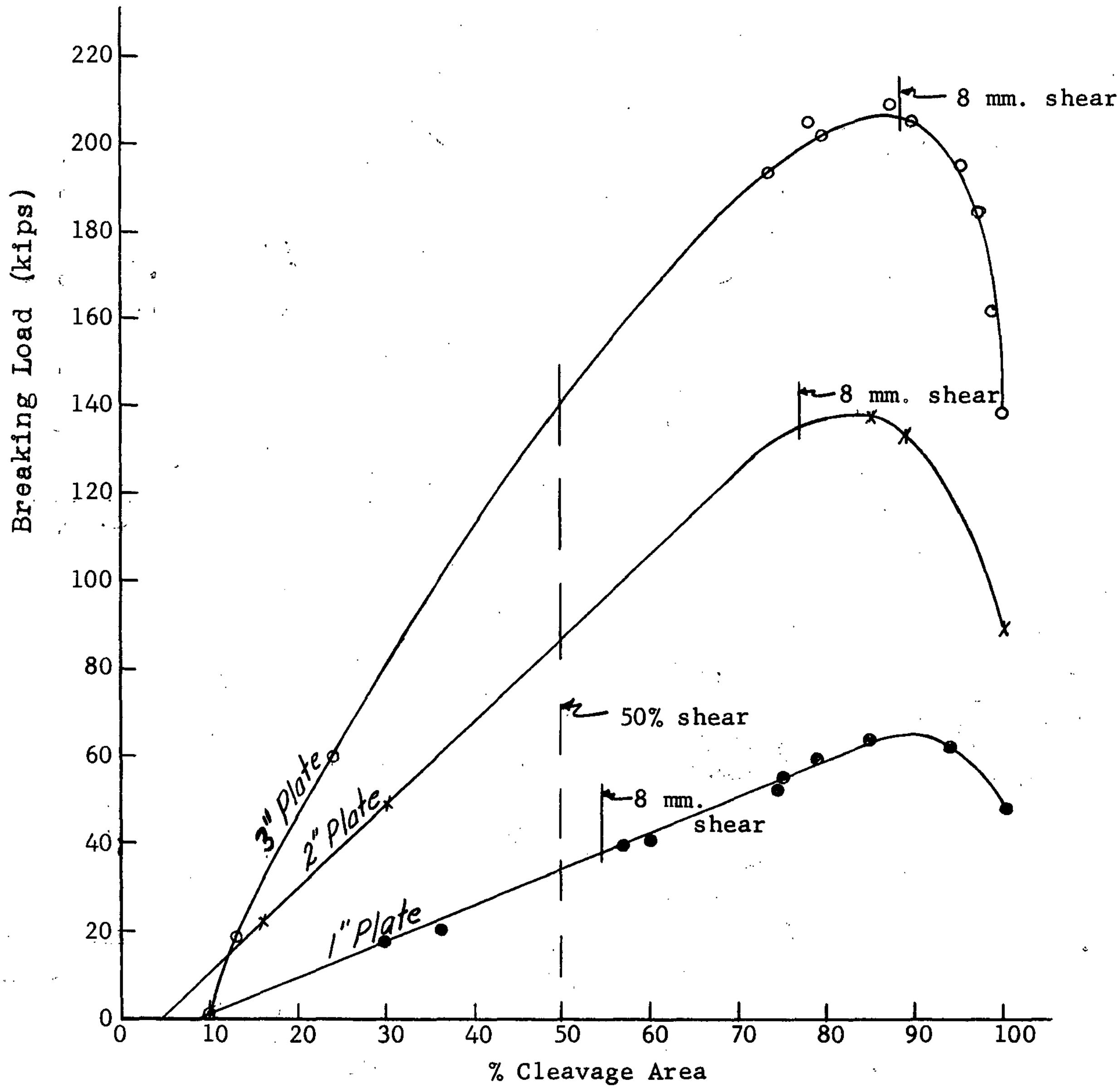


Fig. 8.5 BREAKING LOAD vs. PERCENT CLEAVAGE AREA FOR FULL DEPTH SPECIMENS OF VARYING THICKNESS

Van der Veen Tests

RELATIVE STRESS RATIOS AT 50% SHEAR

Specimen Thickness (inch)	Breaking Load (kips)	Relative Stress Ratio
1	28.0	0.75
2	17.0	0.91
3	7.0	1.00

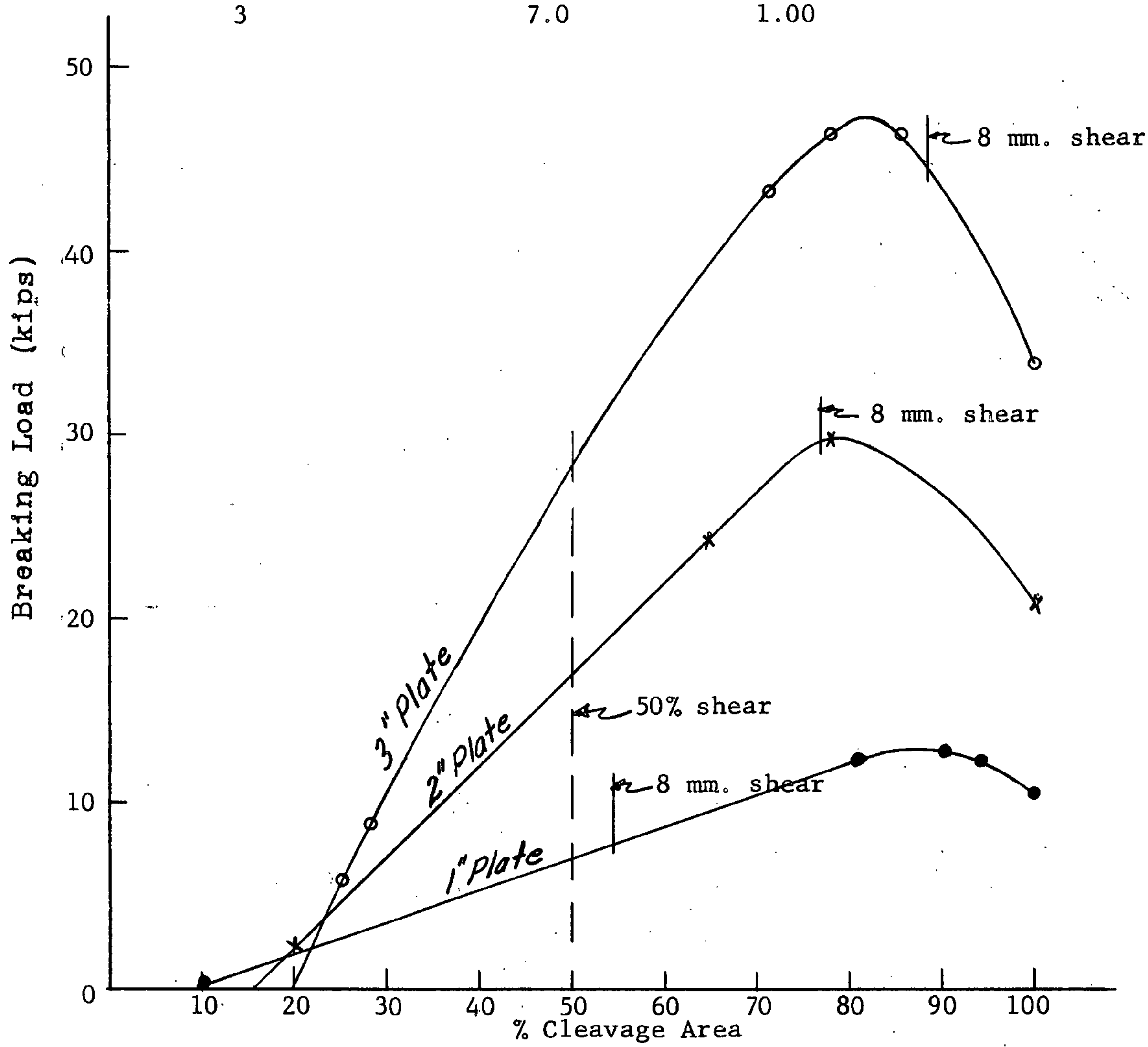


Fig. 8.6 BREAKING LOAD vs. PERCENT CLEAVAGE AREA FOR 1/2 DEPTH SPECIMENS OF VARYING THICKNESS

Van der Veen Tests

RELATIVE STRESS RATIOS AT 50% SHEAR

Specimen Thicnesss (inch)	Breaking Load (kips)	Relative Stress Ratio
1	6.0	0.75
2	3.7	0.92
3	1.5	1.00

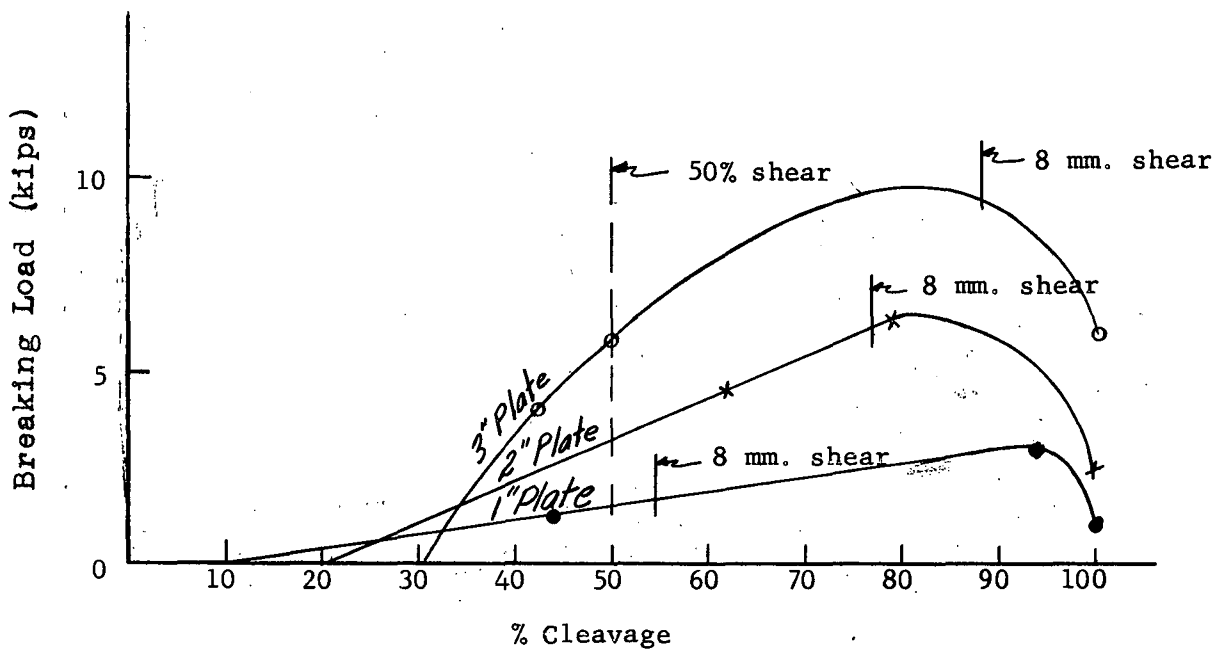


Fig. 8.7 BREAKING LOAD vs. PERCENT CLEAVAGE AREA FOR 1/4 DEPTH SPECIMENS OF VARYING THICKNESS

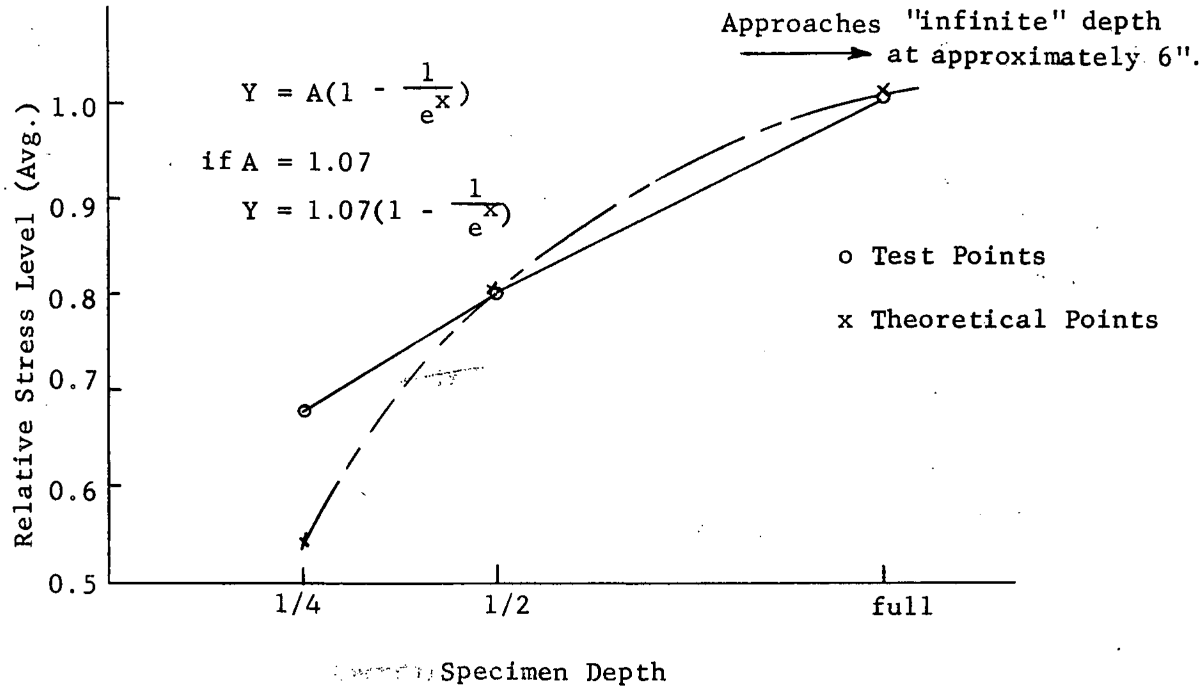


Fig. 8.8 RELATIVE STRESS LEVEL vs. SPECIMEN DEPTH

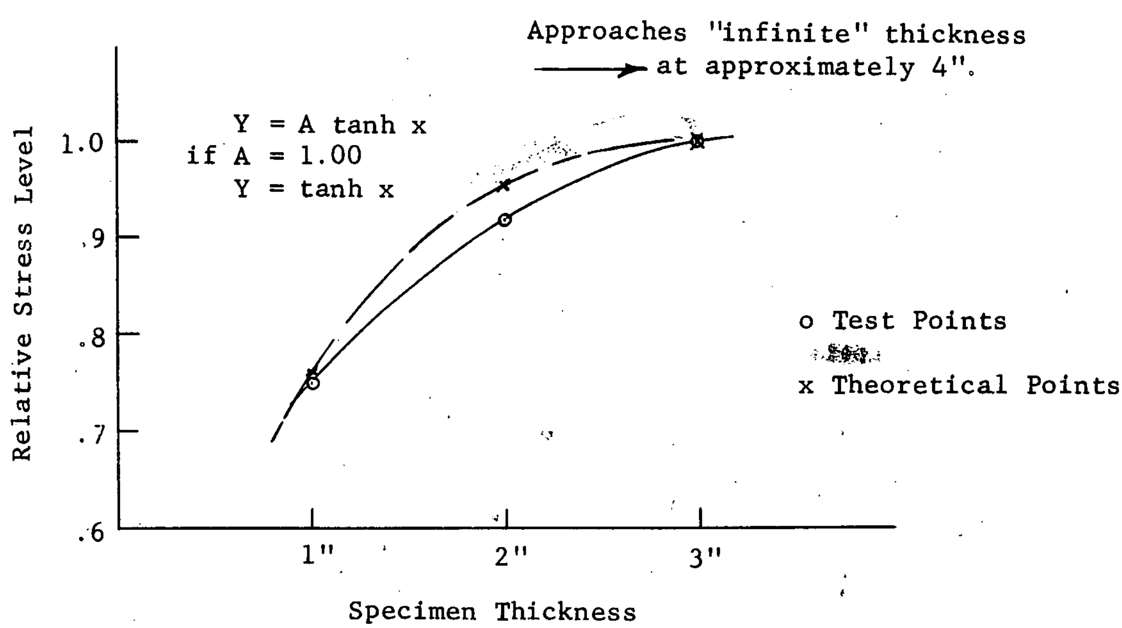


Fig. 8.9 RELATIVE STRESS LEVEL vs. SPECIMEN THICKNESS

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